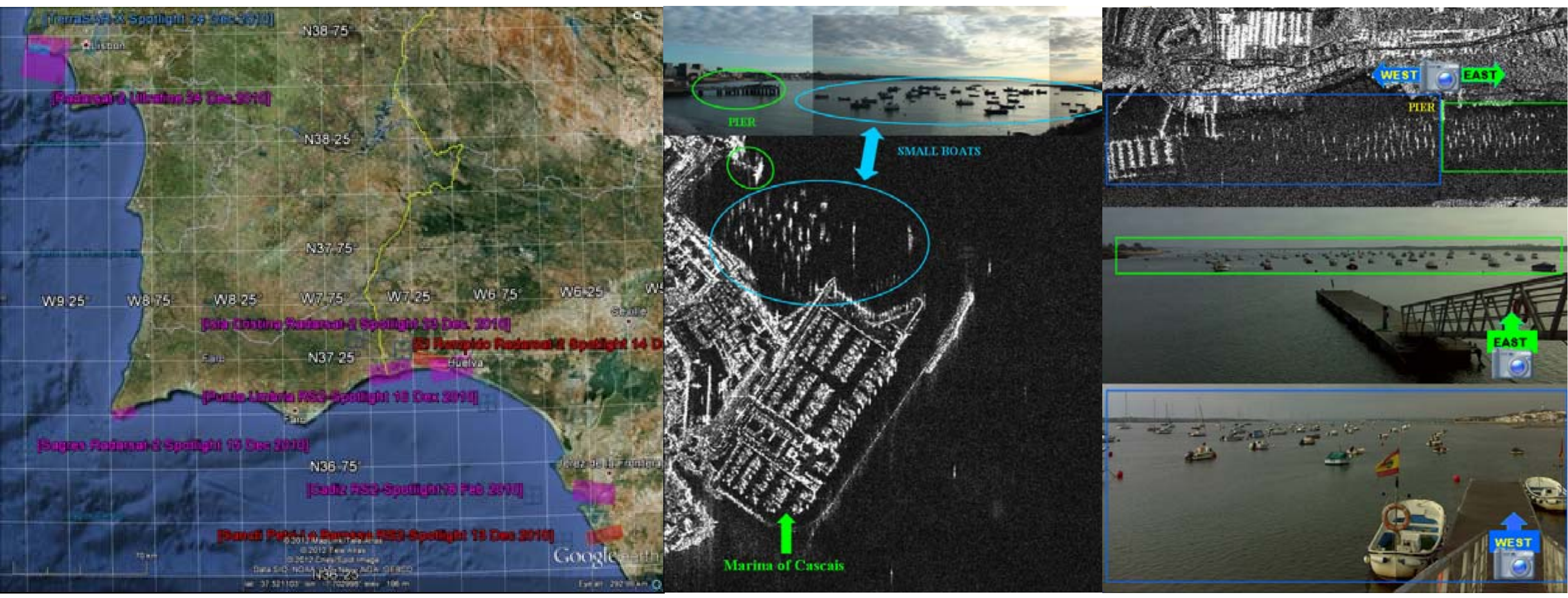
European
Commission

JRC SCIENTIFIC AND POLICY REPORTS

Spaceborne SAR Small Boat Detection Campaign in Portugal and Spain

Results of the Spaceborne SAR Small Boat Detection campaign conducted by the EC-JRC in Portugal and Spain in December 2010

Authors: Victor M.G. Silva
Harm Greidanus



Report EUR 25281 EN

Joint
Research
Centre

European Commission
Joint Research Centre
Institute for the Protection and Security of the Citizen

Contact information
Victor Silva
Address: Joint Research Centre, Via Enrico Fermi 2749, TP 670, 21027 Ispra (VA), Italy
E-mail: victor.silva@jrc.ec.europa.eu
Tel.: +39-0332-786709
Fax: +39-0332-789156
http://ipsc.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

JRC70093

EUR 25281 EN

ISBN 978-92-79-22553-6 (pdf)

ISSN 1831-9424 (online)

doi: 10.2788/21761

Luxembourg: Publications Office of the European Union, 2012

Printed in Italy

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

EXECUTIVE SUMMARY

The European maritime area is one of Europe's most important assets with regard to resources, security and ultimately prosperity of the Member States. A significant part of Europe's economy relies directly or indirectly on it. It is not just the shipping or fisheries industries and their related activities. It is also shipbuilding and ports, marine equipment and offshore energy, maritime and coastal tourism, aquaculture, submarine telecommunications, blue biotech and the protection of the marine environment. The European maritime area faces several risks and threats posed by unlawful activities, such as drugs trafficking, smuggling, illegal immigration, organised crime and terrorism. Piracy in international waters also constitutes a threat to Europe since it can disrupt the maritime transport chain. These risks and threats can endanger human lives, marine resources and the environment, as well as significantly disrupt the transport chain and global and local security. It is anticipated that these risks and threats will endure in the mid and long run. In order to keep Europe as a world leader in the global maritime economy, an effective integrated/interoperable, sustainable maritime surveillance system and situational awareness are needed.

A significant number of unlawful maritime activities, such as illegal immigration, drugs trafficking, smuggling, piracy and terrorism involve mainly small boats, because small boats are faster and more difficult to detect using conventional means. Hence, it is very important to find out the feasibility of using SAR Satellite images for small boat detection. Since 2008 the EC-JRC has carried out a number of SAR Small Boat detection experiments to assess the feasibility of using Spaceborne SAR for Small Boat detection. This report presents the results and conclusions of the Spaceborne SAR Small Boat detection campaign in inland sea waters and coastal waters carried out by the EC-JRC in the South of Spain (Sancti Petri-La Barrosa, El Rompido, Punta Umbria, Cadiz and Isla Cristina) and in Portugal (Sagres and Cascais) from 13 to 24 December 2010.

The results of this spaceborne SAR small boat detection experiment on inland sea waters and coastal waters show that under suitable conditions of sea state, wind speed and incidence angle it is possible to detect small boats in spaceborne SAR imagery. In all eight spaceborne SAR images acquired during this experiment it was possible to detect most small boats available at the time of the satellites overpass. Further research is needed to investigate if an empirical probability of small boat detection in spaceborne SAR imagery can be established as a function of sea state, wind speed, incidence angle and other relevant parameters. Such research may involve setting up a significant number of small boat detection controlled experiments or through simulation using adequate Monte Carlo simulations, or both.

1. – Introduction

This report presents the key findings of the SAR Satellite Imagery Small Boat Detection Campaign, carried out by the EC-JRC in Portugal (Cascais and Algarve) and Spain (Sancti Petri-La Barrosa, El Rompido, Punta Umbria, Cadiz, Huelva and Isla Cristina) from 13 to 24 December 2010.

1.1 – Scope

This study addresses the feasibility of using Synthetic Aperture Radar (SAR) Satellite imagery for Small Boat Detection, in particular on inland and coastal sea waters.

To answer this statement of work, the European Commission (EC) – Joint Research Centre (JRC) set up a small boat detection campaign in the Portugal (Cascais and Algarve) and Spain (Sancti Petri-LaBarossa, El Rompido, Punta Umbria, Cadiz, Huelva and Isla Cristina) on inland and coastal sea waters. In most previous small boat detection campaigns carried out by the EC-JRC, namely in Algeria & Italy (2008), in cooperation with Frontex and national authorities in Sardinia-Italy, Palomares Canyon–Spain (Sep./Oct.2009) and in Portoroz-Slovenia (May/Jun. 2010), the trials took place on open sea and on land (beach). In order to reduce the effect of the sea state (sea clutter) to the minimum possible, the EC-JRC set up a Small Boat detection campaign on inland waters in the Algarve-Portugal (Dec.2009) where the sea state does not play an important role because inland sea waters are protected from the effects of the tides and the currents. This time the experiment took place on inland and on coastal sea waters in Portugal and Spain to further assess the feasibility of using spaceborne SAR for small boat detection on inland and coastal waters. With this new experiment the EC-JRC covers the most common relevant sea scenarios, namely open sea, inland sea waters and coastal waters.

1.2 – Objectives

The work was performed with the following objectives:

- To assess the feasibility of detection of Small Boats in Synthetic Aperture Radar (SAR) Satellite imagery (Radarsat2 and TerraSAR-X), in particular on inland and coastal sea waters.
- To try to characterise the SAR signature of Small Boats in SAR Satellite imagery.
- To identify the limitations of current State-of-the-Art SAR Satellite technology for maritime surveillance, in particular for Small Boat detection.

1.3 – Context

Problem Statement – The European maritime area is one of Europe's most important assets with regard to resources, security and ultimately prosperity of the Member States. A significant part of Europe's economy relies directly or indirectly on it. It is not just the shipping or fisheries industries and their related activities. It is also shipbuilding and ports, marine equipment and offshore energy, maritime and coastal tourism, aquaculture, submarine telecommunications, blue biotech and the protection of the marine environment. The European maritime area faces several risks and threats posed by unlawful activities, such as drugs trafficking, smuggling, illegal immigration, organised crime and terrorism. Piracy in international waters also constitutes a threat to Europe since it can disrupt the maritime transport chain. These risks and threats can endanger human lives, marine resources and the environment, as well as significantly disrupt the transport chain and global and local security. It is anticipated that these risks and threats will endure in the mid and long run. In order to keep Europe as a world leader in the global maritime economy, an effective integrated/interoperable, sustainable maritime surveillance system and situational awareness are needed.

A significant number of unlawful maritime activities, such as illegal immigration, drugs trafficking, smuggling, piracy and terrorism involve mainly small boats, because small boats are faster and more difficult to detect using conventional means. Hence, it is very important to find out the feasibility of using SAR Satellite images for small boat detection.

Figures 1 and 2 illustrate the main maritime security and safety threats, namely Piracy, Terrorist/Military Threats, Weapons Proliferation/Smuggling, Security of Critical Infrastructures, Containers Security, Illegal Fishing, Drugs Trafficking, and Illegal Immigration. A common element to most of these unlawful maritime activities is the use of small boats. That is the main reason why it is so important to assess the feasibility of using spaceborne SAR and other technologies (e.g. EO/IR, other sensors, UAS, other platforms, etc.) for small boat detection, classification and identification.

Figure 3 illustrates the Common Operational Picture (COP) required for Maritime Domain Awareness to provide Quick Reaction Assessment (QRA) which leads to Decisions and Actions. As it can be seen, the Common Operational Picture (COP) is built based on information provided by a Maritime Surveillance System. In fact, this System is made up of the integration of several systems (System of Systems). The different systems involved can be categorised into several groups, namely 1.)– Reporting Systems, 2.)– Sensors, 3.)– Platforms, 4.)– Communications, 5.)– Data Fusion & Sharing, 6.)- Intelligence and Data Bases. The most relevant components of each group are indicated in figure 3.

Figure 4 illustrates the mapping of the main maritime security threats and gaps, as well as the main priorities in terms of the different technologies involved in maritime surveillance. For each maritime threat, the technologies required to fill in each gap is indicated and its priority is expressed in a range of numbers (1 to 3, 1 = Maximum Priority, 2 = Medium Priority, 3 = Low Priority) and colours (Red = Maximum Priority, Orange = Medium Priority, Green = Low Priority). The main technologies involved in maritime surveillance are listed on the bottom of figure 4 and are reproduced here for convenience of the reader: 1.- Reporting Systems, 2.- Sensors, 3.- Platforms, 4.- Communications, 5.- Data Fusion & Sharing, 6.- Intelligence and 7.- Databases. For example, the mitigation of the main threat Piracy requires filling in several maritime security gaps (e.g. lack of persistent surveillance, lack of wide-are maritime surveillance, lack of small boat detection, lack of Early Warning Systems, and lack of Information Sharing with maximum priority (1- Red) and among the required technologies listed are UAS, LTAAV, GEO-HR, etc. Concerning the remaining two gaps (Limited Interoperability and Containers Security) they are less relevant to mitigate Piracy, hence the priority for Limited Interoperability is 2-Orange and for Containers Security is 3- Green.

Main Maritime Security Threats

●1.) – Piracy

● 2.) – Terrorist / Military Threats

● 3.) – Weapons Proliferation/Smuggling

● 4.) – Security of Critical Infrastructures

Figure 1 – Main Maritime Security and Safety Threats. This figure illustrates Piracy, Terrorist and Military Threats, Weapons proliferation/Smuggling and Security o Critical Infrastructures.

Main Maritime Security Threats

- 5.) – Containers Security

- 6.) – Illegal Fishing (increases Piracy?)

- 7.) – Drugs Trafficking

- 8.) – Illegal Migration

Figure 2 – Main Maritime Security and Safety Threats. This figure illustrates Containers Security, Illegal Fishing, Drugs Trafficking and Illegal Immigration.

Maritime Domain Awareness (MDA)

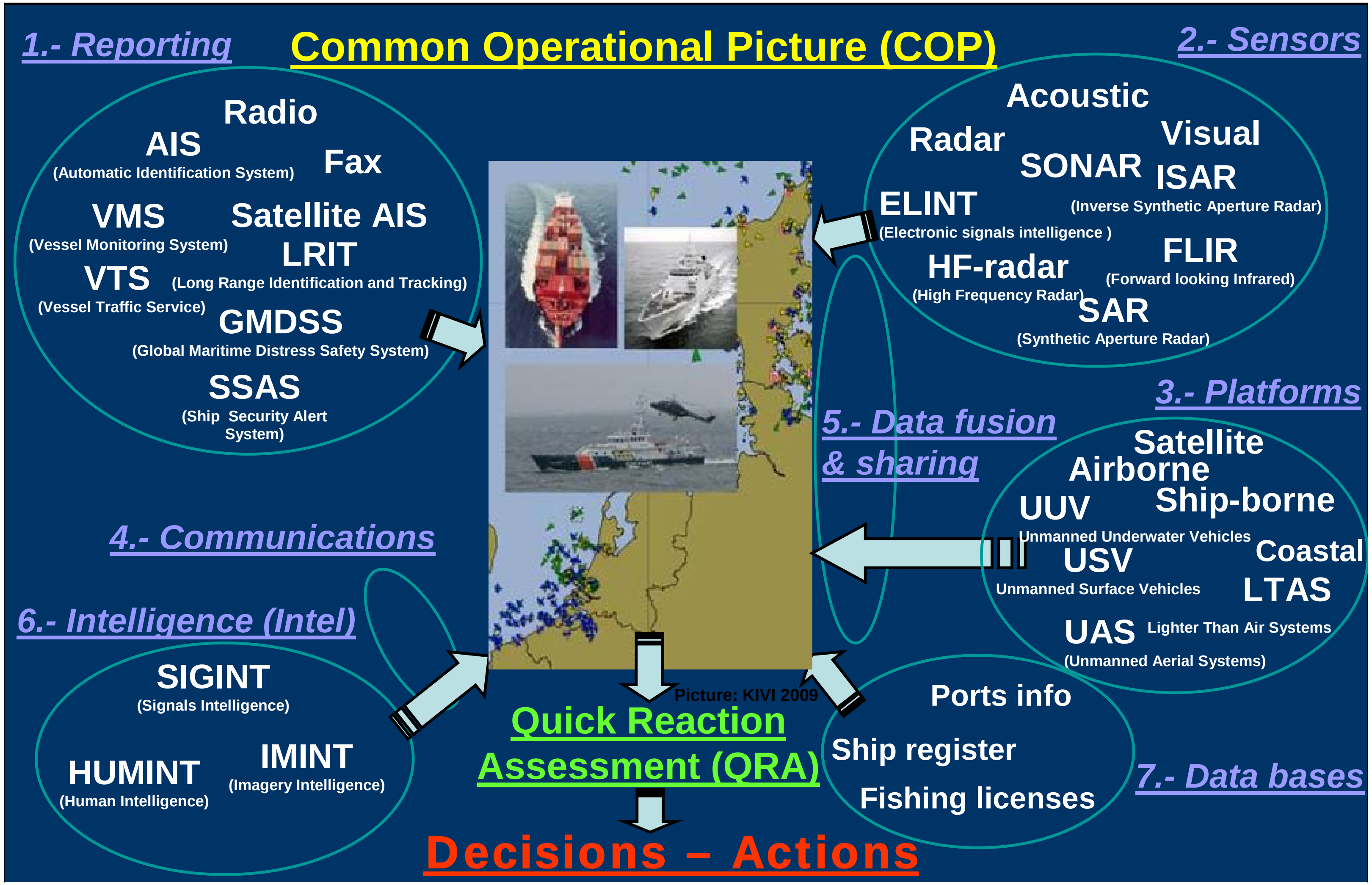


Figure 3 – Maritime Domain Awareness (MDA) – Common Operational Picture (COP). Maritime Surveillance System of Systems.

Maritime Security Main Threats / Gaps

Gaps→ / ↓Threats	Lack of Risk Assessment Capability	Lack of Persistent Surveillance	Lack of Wide-Area surveillance	Lack of Small Boat Detection	Lack of Early Warning Systems	Lack of Information Sharing	Limited Interoperability	Lack of Containers Security
• Piracy	UAS, LTAV,GEO-HR + ...	UAS, LTAV,GEO-HR + ...	SAR, GEO-HR + ...	UAS, USV, LTAV + ...	UAS, LTAV, + ...	Coordination & Sharing + ...	Interoperability Optimisation + ...	
	1, 2, 3, 5, 6, 7	1, 2, 3, 5, 6, 7	1, 2, 3, 5, 6	1, 2, 3	1,2,3,4,5,6	4,5,6,7	1,2,3,4,5,6,7	1,2,3,4,5,6,7
• Terrorism	UAS, LTAV,GEO-HR + ...	UAS, LTAV, GEO-HR + ...	SAR, AIS GEO-HR + ...	UAS, USV, LTAV + ...	Intelligence + ...	Intelligence + ...	Interoperability Optimisation + ...	Intelligence + ...
	1, 2, 3, 5, 6, 7	1, 2, 3, 5, 6	1, 2, 3, 5, 6	1, 2, 3	1,2,3,4,5,6	4,5,6,7	1,2,3,4,5,6,7	1,2,3,4,5,6,7
• Weapons of Mass Destruction Smuggling	UAS, LTAV,GEO-HR + ...	UAS, LTAV,GEO-HR + ...	SAR, AIS + ...	UAS, USV, LTAV + ...	Intelligence + ...	Intelligence + ...	Intelligence + ...	Intelligence + ...
	1, 2, 3, 5, 6, 7	1, 2, 3, 5, 6	1, 2, 3, 5, 6	1, 2, 3	1,2,3,4,5,6	4,5,6,7	1,2,3,4,5,6,7	1,2,3,4,5,6,7
• Drugs Trafficking	UAS, LTAV,GEO-HR + ...	UAS, LTAV,GEO-HR + ...	SAR, AIS + ...	UAS, USV, LTAV + ...	Intelligence + ...	Intelligence + ...	Intelligence + ...	Intelligence + ...
	1, 2, 3, 5, 6, 7	1, 2, 3, 5, 6	1, 2, 3, 5, 6	1, 2, 3	1,2,3,4,5,6	4,5,6,7	1,2,3,4,5,6,7	1,2,3,4,5,6,7
• Illegal Immigration	UAS, LTAV,GEO-HR + ...	UAS, LTAV,GEO-HR + ...	SAR, AIS + ...	UAS, USV, LTAV + ...	Intelligence + ...	Intelligence + ...	Intelligence + ...	Intelligence + ...
	1, 2, 3, 5, 6, 7	1, 2, 3, 5, 6	1, 2, 3, 5, 6	1, 2, 3	1,2,3,4,5,6	4,5,6,7	1,2,3,4,5,6,7	1,2,3,4,5,6,7
• Critical Infrastructure Security	UAS, LTAV,GEO-HR + ...	UAS, LTAV,GEO-HR + ...	SAR, AIS + ...	UAS, USV, LTAV + ...	+ ...	Intelligence + ...	Intelligence + ...	Intelligence + ...
	1, 2, 3, 5, 6, 7	1, 2, 3, 6	1, 2, 3, 5, 6	1, 2, 3	1,2,3,4,5,6	4,5,6,7	1,2,3,4,5,6,7	1,2,3,4,5,6,7
• Illegal Fishing	UAS, LTAV,GEO-HR + ...	AIS+SAR, UAS,LTAV + ...	SAR, AIS, GEO-HR+ ...	UAS, USV, LTAV + ...	Intelligence + ...	Intelligence + ...	Intelligence + ...	
	1, 2, 3, 5, 6, 7	1, 2, 3, 5, 7	1, 2, 3, 5, 6	1, 2, 3	1,2,3,4,5,6	4,5,6,7	1,2,3,4,5,6,7	
• Unlawful Use of Containers (Security)	UAS, LTAV,GEO-HR + ...	GPS Tracking + ...			Intelligence + ...	Intelligence + ...		GPS, Intrusion Detection, Seal
	1, 2, 3, 5, 6, 7	4, 6, 7	1, 2, 3, 5, 6	1, 2, 3	1,2,3,4,5,6	4,5,6,7	1,2,3,4,5,6,7	1,2,3,4,5,6,7

(-)	Priority	(+)	Not Relevant

SURVEILLANCE TECHNOLOGIES	1.- Reporting Systems	2.- Sensors	3.- Platforms	4.- Communications	5.- Data Fusion & Sharing	6.- Intelligence	7.- Databases

Figure 4 – Maritime Security Main Threats / Gaps mapping and main technology development priorities to mitigate the Threats by Filing in the Gaps.

2. – Research Method

In order to find out the feasibility of using SAR Satellite imagery to detect small boats, a controlled experiment using targets of opportunity was designed, set up and executed. The controlled experiment is briefly described next.

2.1 – Controlled Experiment on Inland and Coastal Sea Waters

The main objective of this controlled experiment was to find out if small boats used as targets of opportunity, could be detected using spaceborne SAR imagery. Knowing the approximate GPS position of a set of small boats, targets of opportunity, and collecting in-situ ground truth data at the time of the SAR Satellite passes it should be possible to find out if small boats can be detected using spaceborne SAR imagery. In order to maximize the probability of detection, inland and coastal sea waters were chosen to minimize the effect of the sea state (sea clutter) on the detection.

The controlled experiment involved the following steps:

1. – The EC-JRC selected several areas in Portugal (Sagres and Cascais) and Spain (Sacti Petri-La Barossa, El Rompido, Punta Umbria, Cadiz, Huelva and Isla Cristina), where a significant number of small boats were available on inland or coastal sea waters. Fig.5 illustrates the selected areas.

2. – The next step comprised the selection of the spaceborne SAR images (Radarsat2-Spotlight and Ultrafine, TerraSAR-X- Spotlight) available between 13 and 24 Dec. 2010 covering the above mentioned locations.

3. - The EC-JRC collected in-situ ground truth data in Portugal and Spain in all the selected locations on the dates and at the times of the satellite passes. The Ground Truth data included photos, videos, the approximate GPS position of the small boats and the weather conditions.

4. – The EC-JRC analysed the SAR satellite images acquired with the Ground Truth data collected during the experiment.

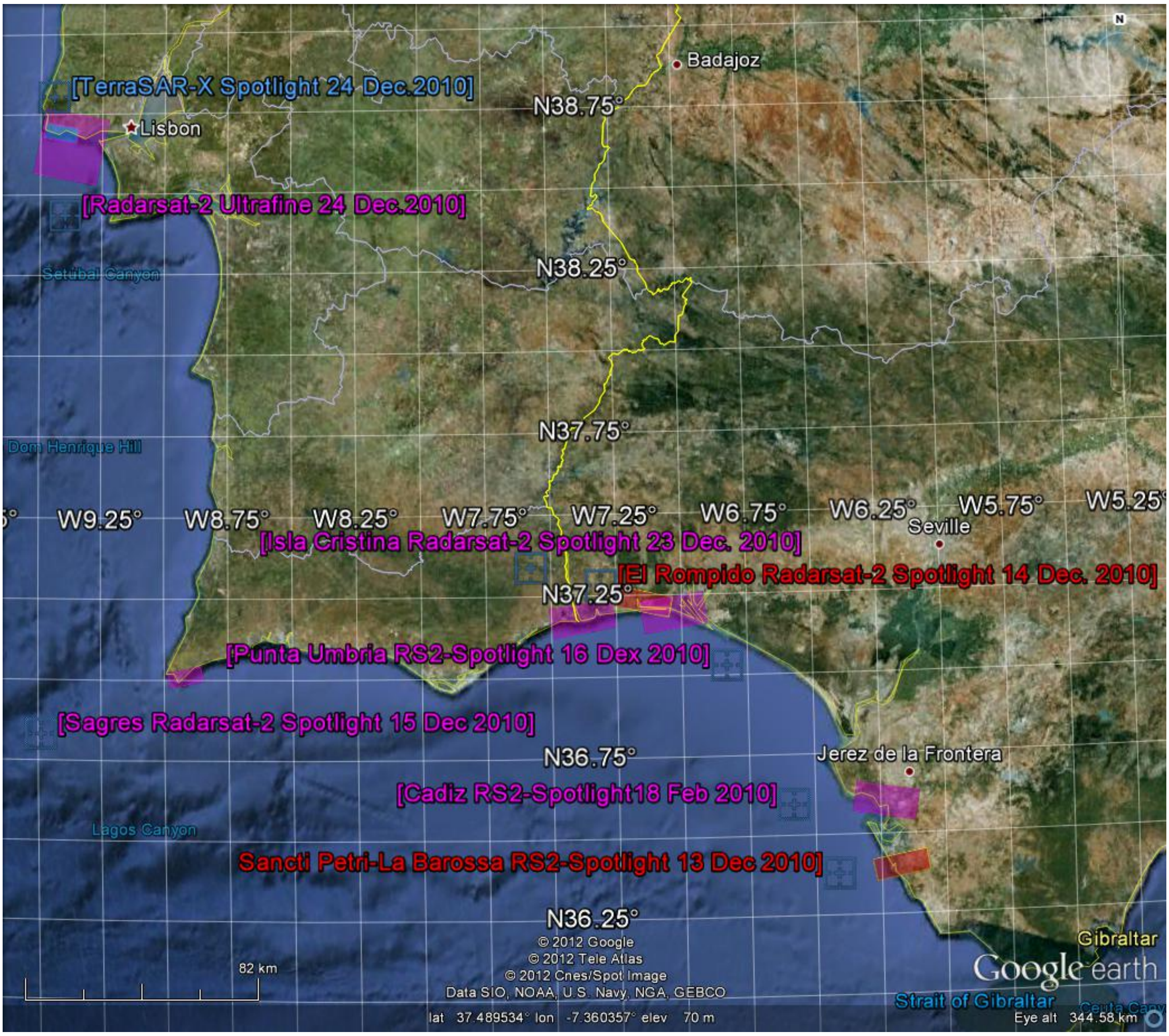


Figure 5 – The selected locations for the experiment in Portugal were:Sagres and Cascais. In Spain the selected sites were Isla Cristina, El Rompido, Punta Umbria, Cadiz and Sancti Petri-La Barrosa.The images and image modes, as well as the dates of acquisition of all spaceborne SAR images acquired are indicated in the map above.

Tabel 1 gives a list of all SAR Satellite images acquired during the Small Boat detection campaign in Portugal and Spain.

Table 1– List of SAR Satellite Imagery Acquired from 13-24 December 2010 in Portugal and Spain.

SAR Satellite Imagery	SAR Image Modes	Polariz.	Place Covered	Date
Radarsat-2	Spotlight	HH	Sancti Petri-La Barrosa-SP	13Dec.2010
Radarsat-2	Spotlight	HH	El Rompido – Spain	14Dec.2010
TerraSAR-X	Spotlight	HH	Sagres - Portugal	15Dec.2010
Radarsat-2	Spotlight	HH	Punta Umbria – Spain	16Dec.2010
Radarsat-2	Spotlight	HH	Cadiz – Spain	18Dec.2010
Radarsat-2	Spotlight	HH	Isla Cristina – Spain	23Dec.2010
Radarsat-2	Ultrafine	HH	Cascais – Portugal	24Dec.2010
TerraSAR-X	Spotlight	HH	Cascais - Portugal	24Dec.2010

3. – Experiment Set Up

In this section we describe the experiment set up, namely the experiment site selection and the SAR Satellite Imagery planning.

3.1 – Experiment Site Selection – Inland Sea Waters

The previous JRC small boat detection campaigns (Algeria, Sardinia and Palomares Canyon) took place mainly on open sea where the sea clutter is relatively high. Bearing in mind that sea clutter plays an important role in SAR imagery small boat detection, making it more difficult, the selection of inland sea water site scenarios for the experiment was an obvious option. By selecting inland sea waters where the sea is flat most of the time the sea clutter effect was minimised.

3.1.1 – Site Selection Criteria

The main criteria used for site selection were the following:

1.) – The sites should have inland sea waters somehow naturally protected from tides and currents in order to minimise the effect of the sea state (clutter) in SAR Small Boat detection.

2.) – The sites should have a reasonable number (over 20) of Small Boats with sizes ranging from 5 up to 20 meters.

3.) – A significant number of Small Boats should be spread over the area, moored on sea at reasonable distances apart from each other to avoid SAR signature contamination.

4.) – The sites should have easy access to facilitate the collection of Ground-Truth data.

3.1.2 – Inland sea waters in Sancti Petri-La Barrosa (Spain)

Sancti Petri-La Barrosa near Cadiz-Spain was the first location selected for the experiment. The area was selected due to the inland sea waters and the availability of small boats that could be used as targets of opportunity. The spaceborne SAR image acquired over Sancti Petri-La Barrosa was a Radarsat2-Spotlight. The frame (footprint) of the SAR image acquired over Sancti Petri-La Barrosa is illustrated in Figure.6.

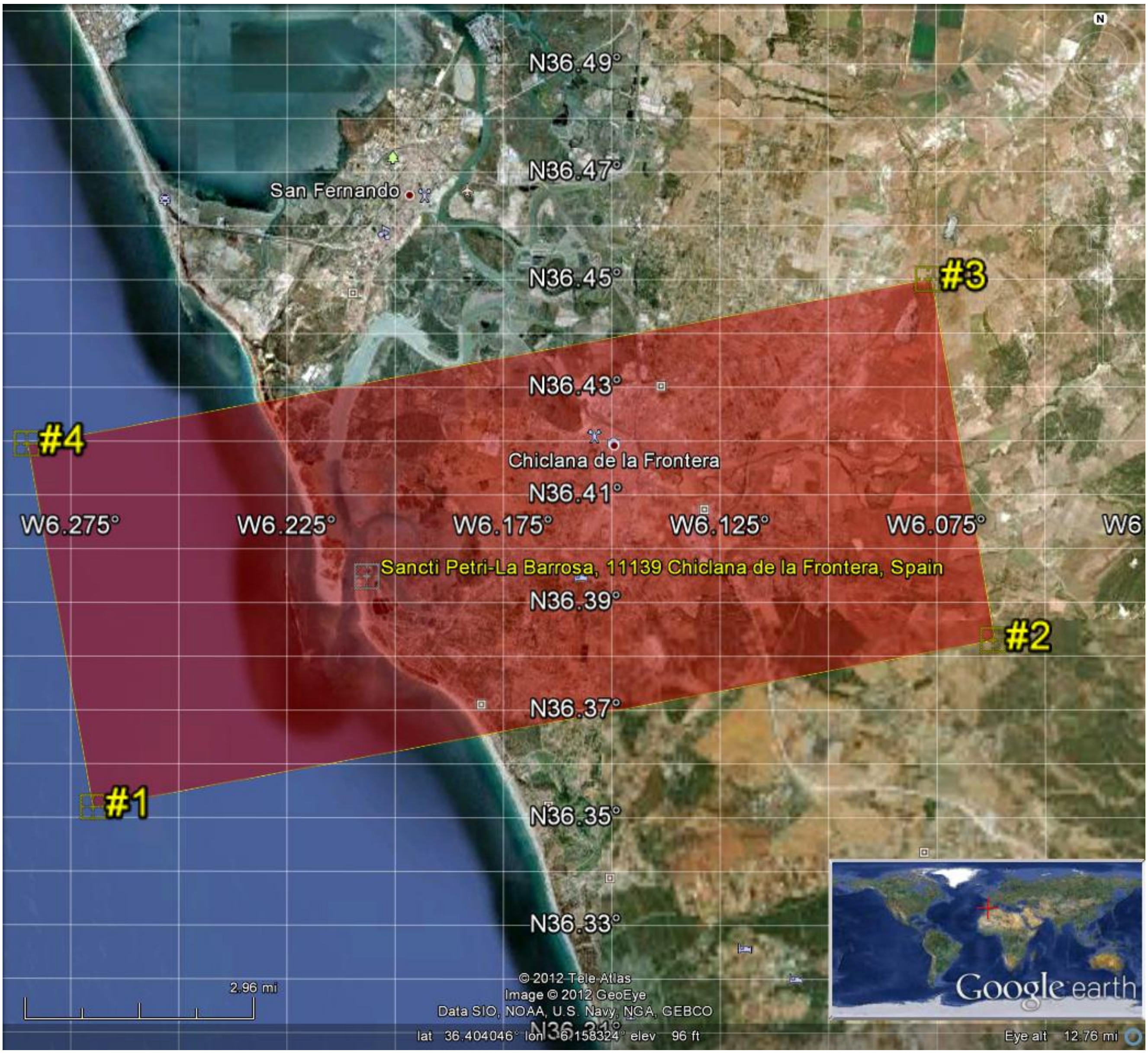


Figure 6 – The first spaceborne SAR image above illustrated was acquired over Sancti Petri-La Barrosa (Spain). The image was a Radarsat2-Spotlight.

Figure.7, a Google Earth image, illustrates the area of Sancti Petri-La Barrosa near Cadiz-Spain. As it can bee seen, a significant number of small boats can be found moored in inland sea waters. The small boats are not packed nor too close to each other, which is essential to avoid SAR signature contamination.

Figure 7 -The Google Earth image above illustrates the area of Sancti Petri-La Barrosa near Cadiz-Spain, over which the first spaceborne SAR image was acquired on 13 Dec. 2010.

3.1.3 – Inland sea waters in El Rompido-Spain

The second inland sea waters site selected for the experiment was in El-Rompido-Spain, illustrated in Figure. 8. The area was selected due to the inland sea waters and the availability of small boats that could be used as targets of opportunity. The spaceborne SAR image acquired over El-Rompido was a RAdarsat2-Spotlight. The frame (footprint) of the SAR image acquired over El-Rompido is illustrated in Figure.8 in red.

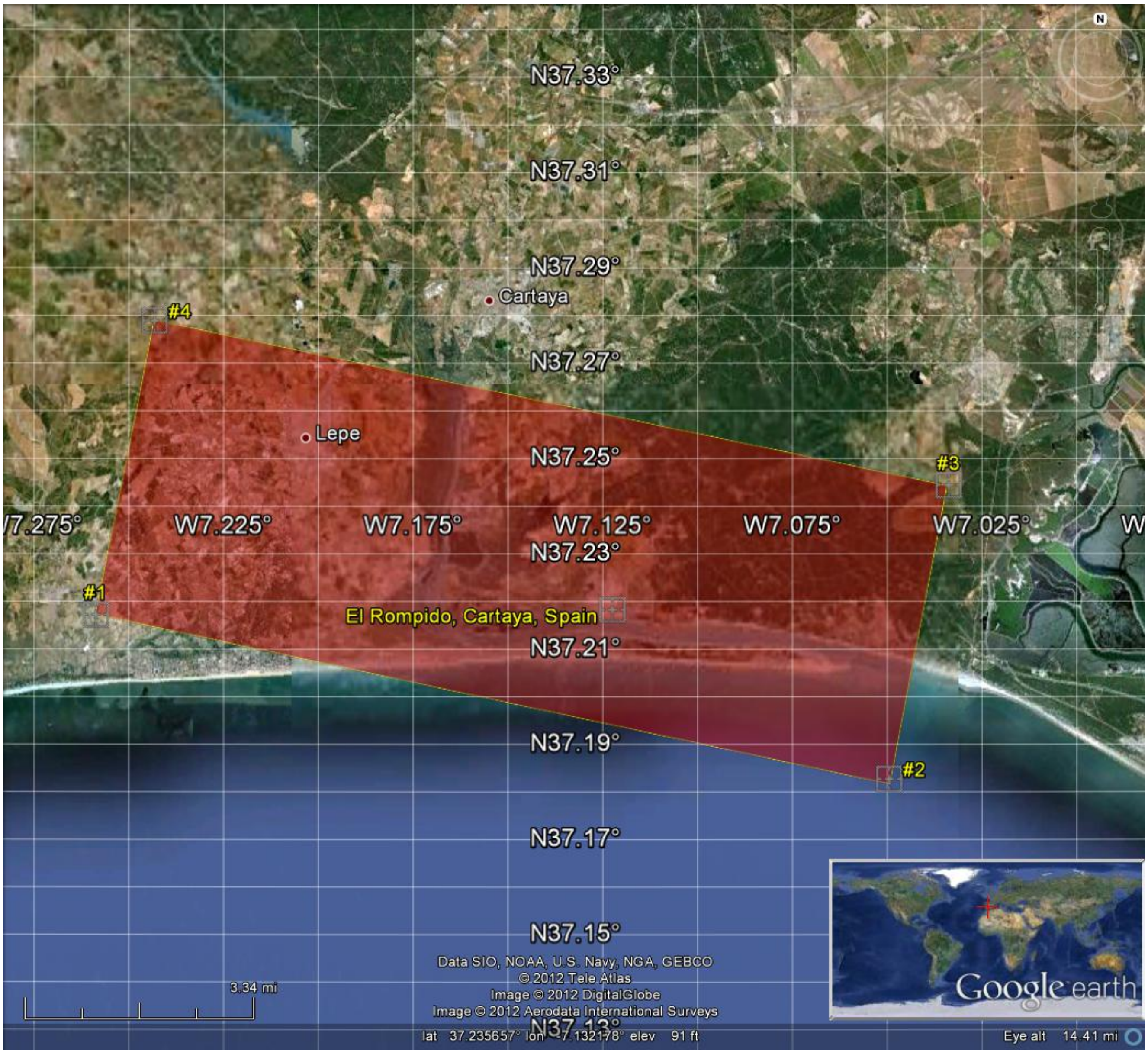


Figure 8 -The Google Earth image above illustrates the area of El-Rompido-Spain, over which the second spaceborne SAR image was acquired on 14 Dec. 2010.

As it can be seen in Figure.9, a large number of small boats with sizes ranging from 3 up to 15 meters can be found in El-Rompido on inland sea waters. The small boats were not packed, which is important to prevent SAR signature contamination. The area was selected due to the inland sea waters and the availability of small boats spread over the area that could be used as targets of opportunity. Besides the small boats on sea water, there were also several small boats on land.

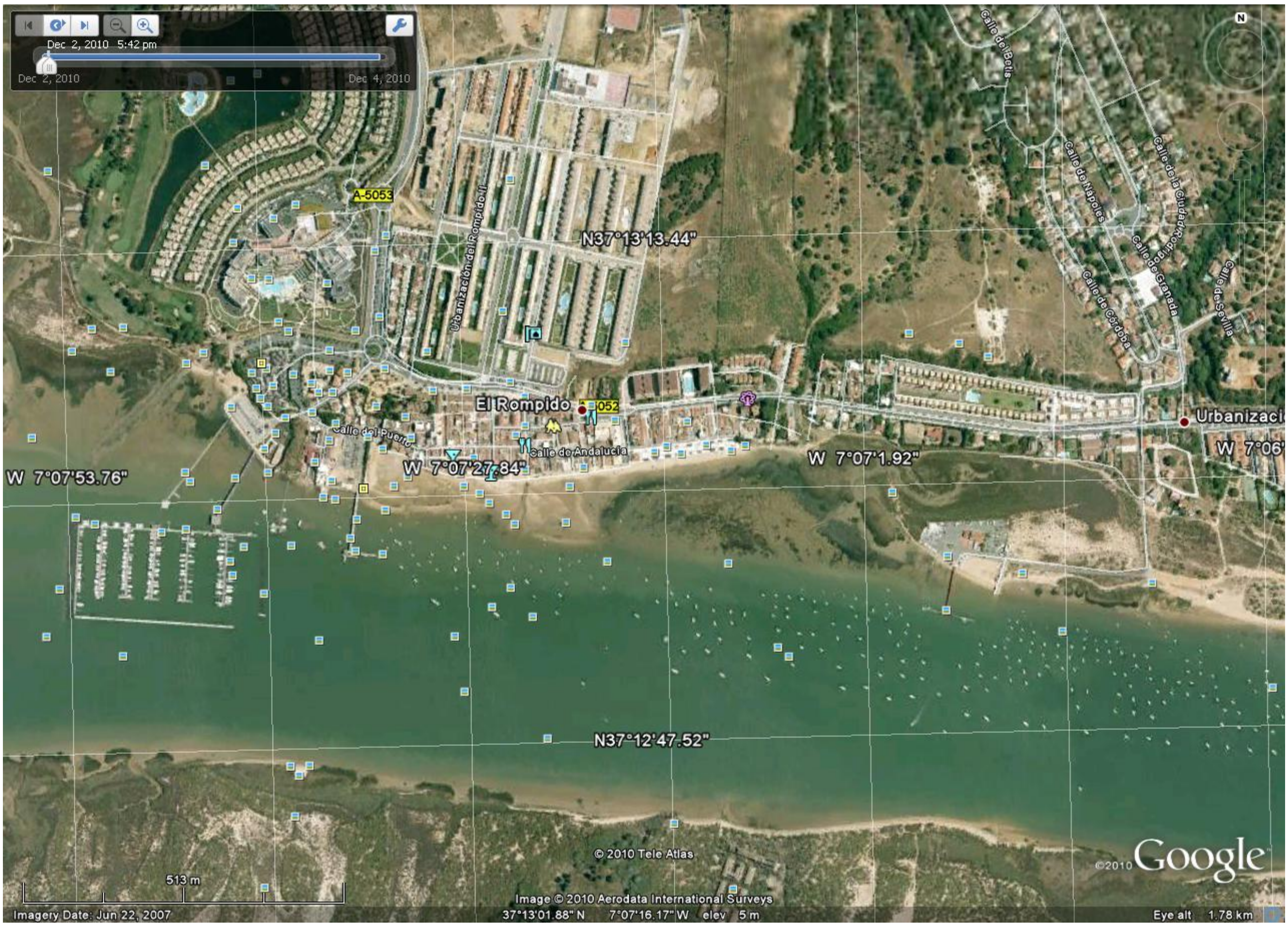


Figure 9 -The Google Earth image above illustrates the area of El-Rompido in Spain, over which the second spaceborne SAR image was acquired on 14 Dec. 2010.

3.1.4 – Port of Sagres-Algarve

The third site selected for the experiment was in Sagres-Algarve, illustrated in Figure. 10. The area was selected because it is representative of coastal/Port waters, which are protected from the sea state effect to some extent, but not as much as inland waters, and due to the availability of small boats that could be used as targets of opportunity. The spaceborne SAR images acquired over Sagres was a TerraSAR-X-Spotlight on 15 December 2010. The frame (footprint) of the SAR image acquired over Sagres is illustrated in Figure.10.

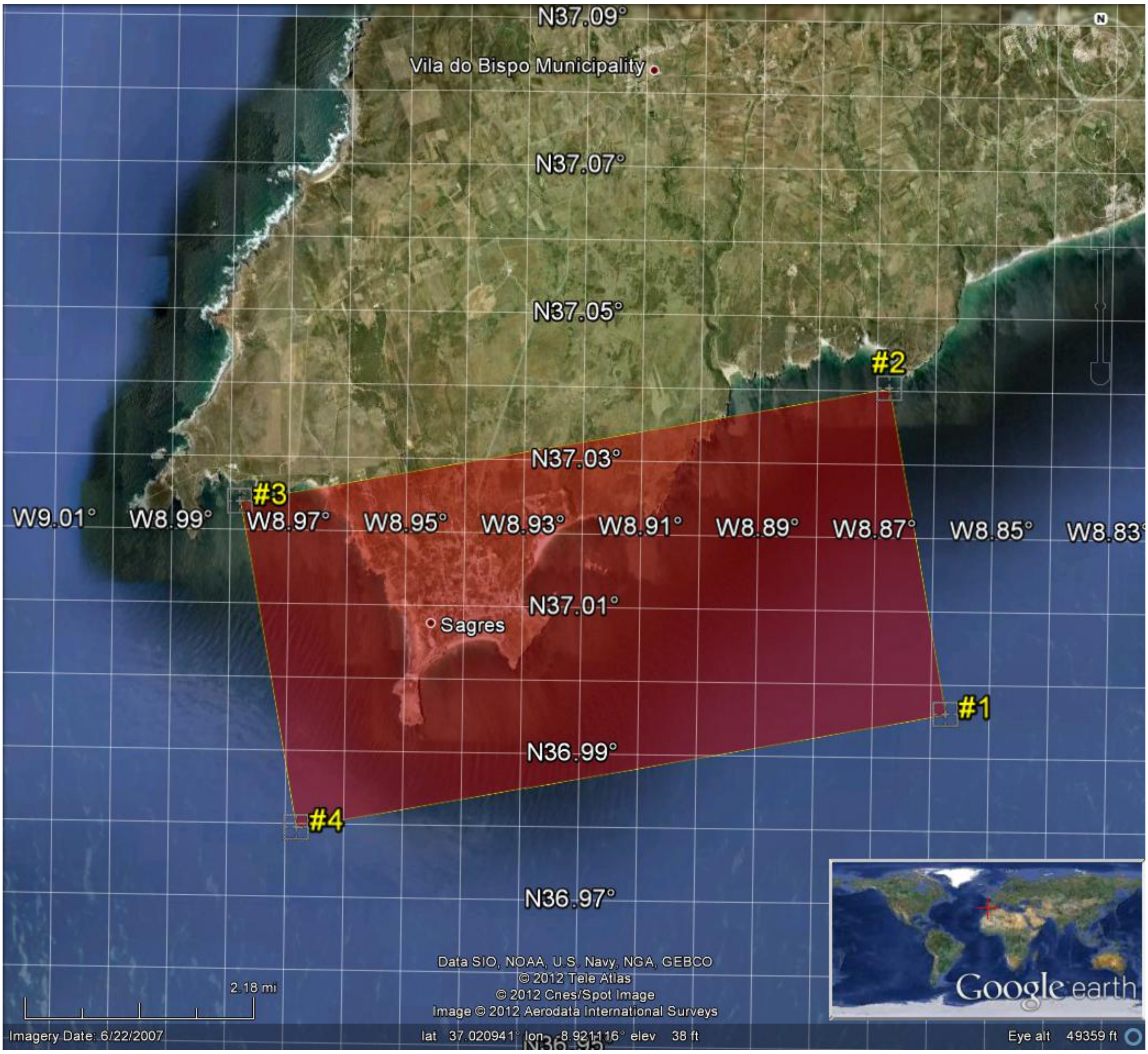


Figure 10 -The Google Earth image above illustrates the area of Sagres-Algarve, over which the third Spaceborne SAR image was acquired on 15 Dec. 2010.

Figure.11 shows a significant number of small boats with sizes ranging from 3 to 10 meters in the Port of Sagres. The small boats were spread over the area of the Port of Sagres. Most of the small boats were not packed or too close to each other, which is important to prevent SAR signature contamination. However, some of the small boats were packed, mainly the ones moored to the piers. The area was selected because it is representative of coastal and Port waters and the availability of small boats spread over the area that could be used as targets of opportunity. Besides the small boats on sea water, there were also several small boats moored at the Port of Sagres.

Figure 11 -The Google Earth image above illustrates the area of Sagres (Port of Sagres) in the Algarve, over which the fourth spaceborne SAR image was acquired on 15 Dec. 2010.

3.1.5 – Inland sea waters in Punta Umbria - Spain

The fourth area selected was Punta Umbria in Spain. Figure.12 illustrates the image frame (footprint) of the SAR image acquired over Punta Umbria - Spain. The area was selected due to the inland sea waters and the availability of small boats that could be used as targets of opportunity. The spaceborne SAR image acquired over Punta Umbria was a Radarsat-2 Spotlight on 16 Decembre 2010.

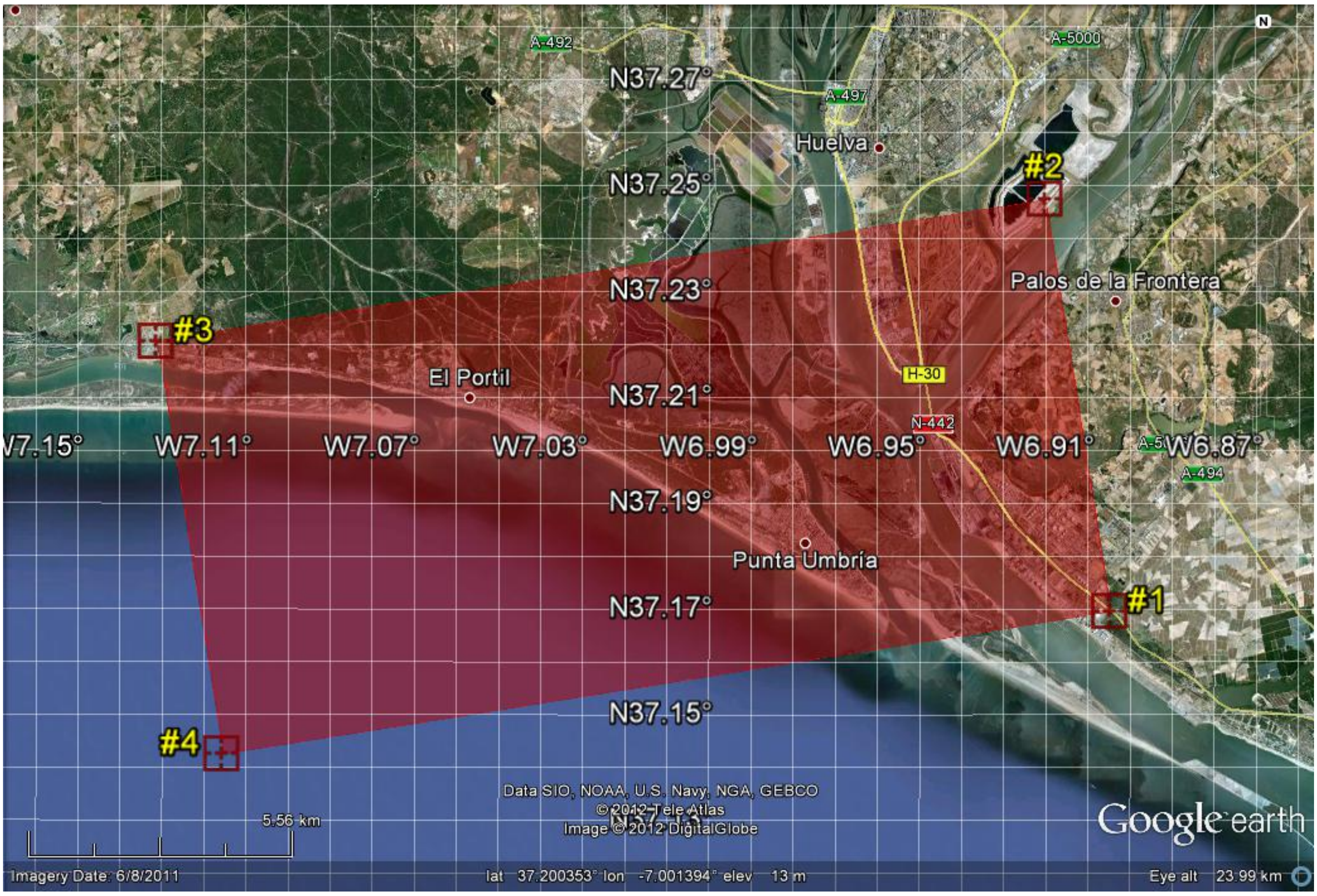


Figure 12 -The Google Earth image above illustrates the area of Punta Umbria - Spain, over which the fourth Spaceborne SAR image was acquired on 16 Dec. 2010.

As it can be seen in Figure.13, a significant number of small boats with sizes ranging from 3 up to 10 meters can be found in Punta Umbria on inland sea waters. It should be noted that the image from Google Earth in Fig. 13 was acquired on 15/08/2007, it was not acquired during the experiment; however, it gives an idea about the type and size of boats that can be found in the area. The small boats were spread over the area along Punta Umbria. They were not packed or too close to each other, which is important to prevent SAR signature contamination. The area was selected due to the inland sea waters and the availability of small boats spread over the area that could be used as targets of opportunity. Besides the small boats on sea water, there were also several small boats on land near Punta Umbria.

Figure 13 -The Google Earth image above illustrates the area of Punta Umbria in Spain, over which the fourth Spaceborne SAR image was acquired on 16 Dec. 2010.

3.1.6 – Inland sea waters in Cadiz-Spain

The fifth area covered was Cadiz in Spain. Figure.14 illustrates the image frame (footprint) of the SAR image acquired over Cadiz-Spain. The area was selected due to the inland sea waters and the availability of small boats that could be used as targets of opportunity. The spaceborne SAR image acquired over Cadiz was a Radarsat2-Spotlight on 18 December 2010.

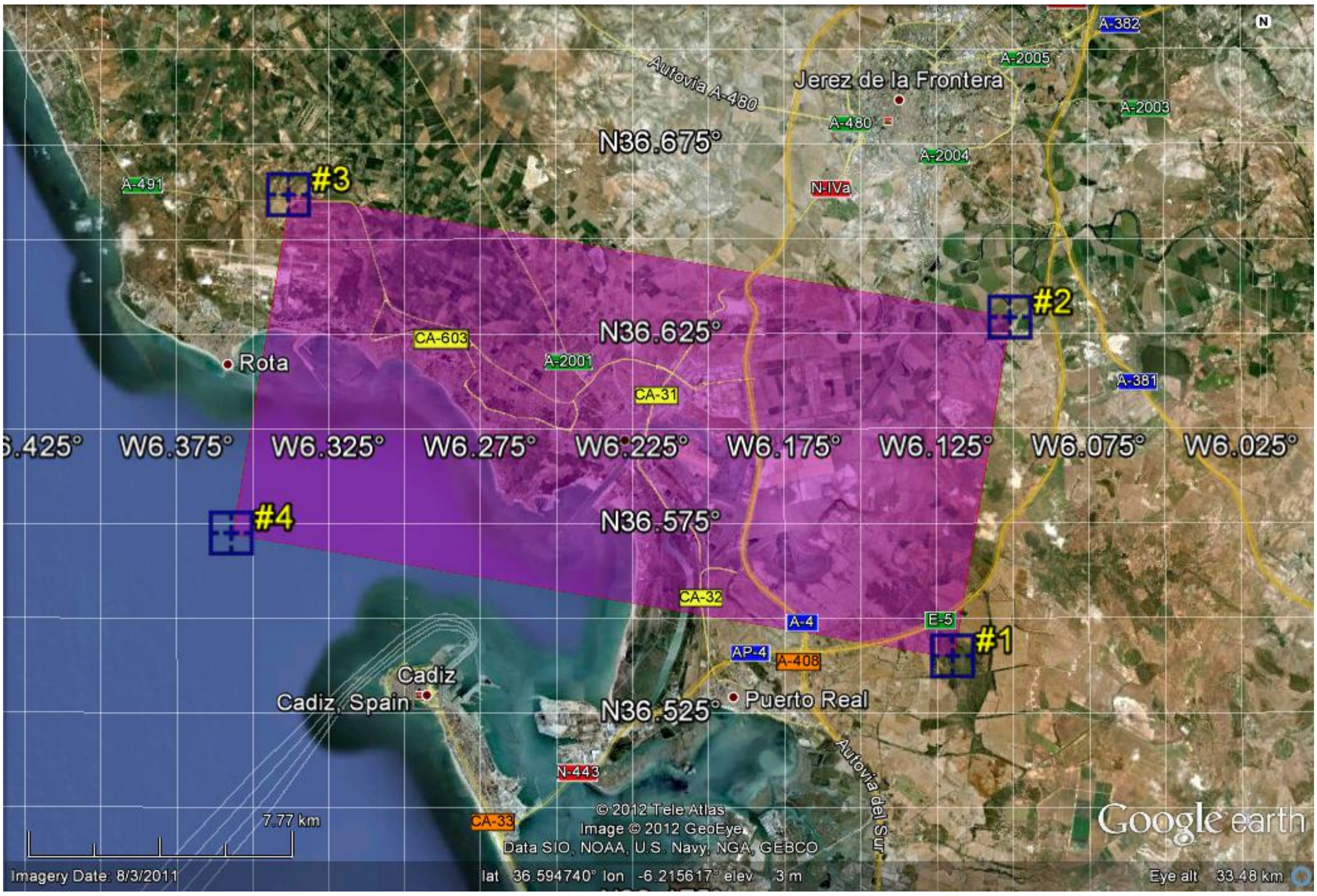


Figure 14 -The Google Earth image above illustrates the area of Cadiz covered by the footprint of the fifth spaceborne SAR image acquired on 18 Dec. 2010.

As it can be seen in Figure.15, a significant number of small boats with sizes ranging from 3 up to 10 meters can be found in Puerto de Santa Maria in Cadiz on inland sea waters. The small boats were spread over the area near Puerto de Santa Maria. Some of the small boats were moored to different piers, other were moored on inland sea waters. Most of the small boats were not packed or too close to each other, which is important to prevent SAR signature contamination. However, some of the boats were close to each other, mainly on piers. The area was selected due to the inland sea waters and the availability of small boats spread over the area that could be used as targets of opportunity. Besides the small boats on sea water, there were also several small boats on land.

Figure 15 -The Google Earth image above illustrates the area of Puerto de Santa Maria, Cadiz in Spain, over which the fifth spaceborne SAR image was acquired on 18 Dec. 2010.

3.1.7 – Inland sea waters in Isla Cristina-Spain

The sixth area selected was Huelva in Spain. Figure.16 illustrates the SAR image footprint of the over the region of Isla Cristina. The area was selected due to the inland sea waters and the availability of small boats that could be used as targets of opportunity. The spaceborne SAR image acquired over Isla Cristina was a Radarsat2-Spotlight on 23 December 2010.

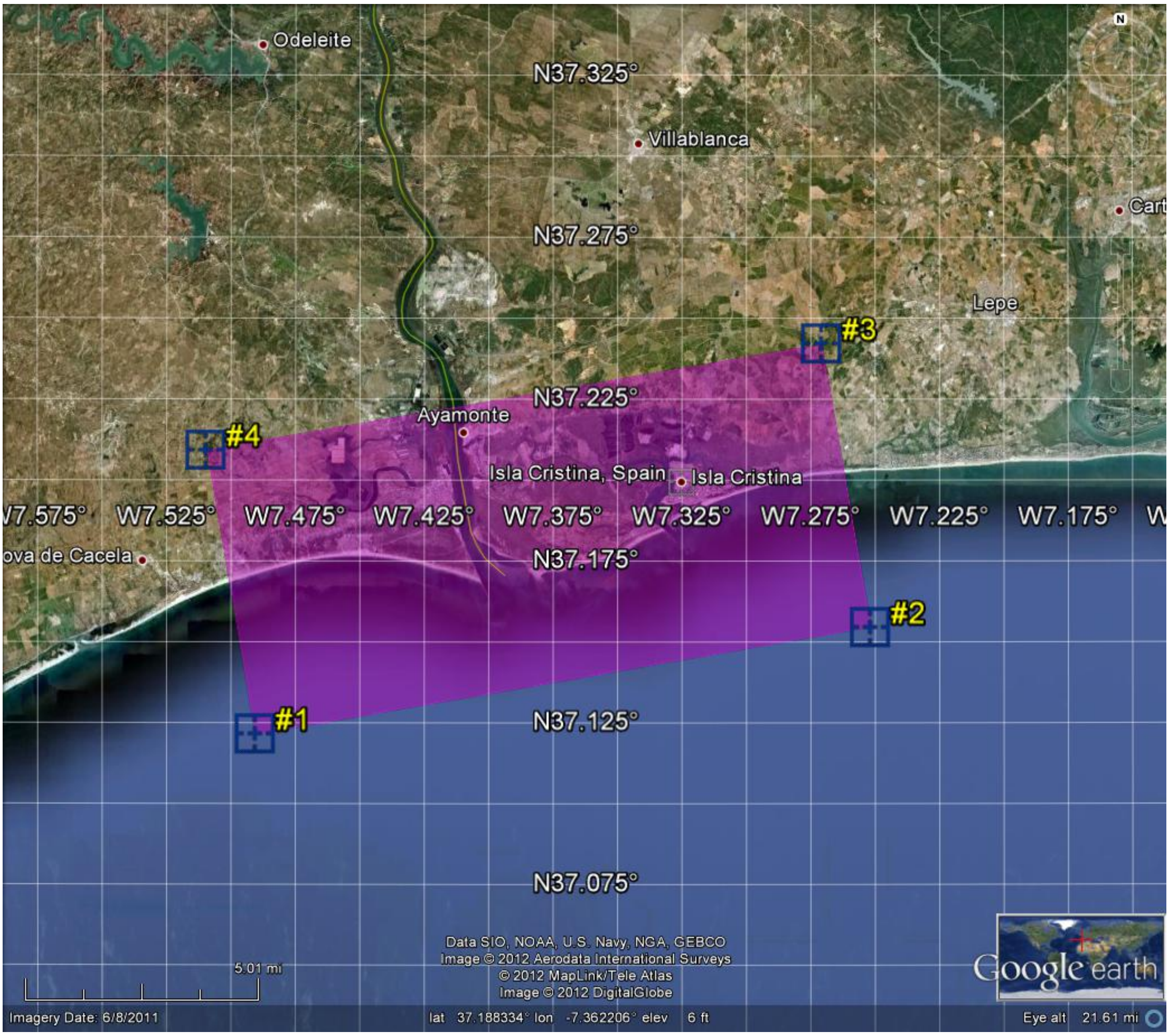


Figure 16 -- The Google Earth image above illustrates the area of Isla Cristina covered by the footprint of the sixth spaceborne SAR image acquired on 23 Dec. 2010.

Figure.17, shows a significant number of small boats with sizes ranging from 3 to 10 meters in Isla Cristina on inland sea waters. The small boats were spread over the area around Isla Cristina Puerto de Santa Maria. Some of the small boats were moored to different piers, other were moored on inland sea waters. Most of the small boats were not packed or too close to each other, which is important to prevent SAR signature contamination. However, some of the boats were close to each other, mainly on piers. The area was selected due to the inland sea waters and the availability of small boats spread over the area that could be used as targets of opportunity. Besides the small boats on sea water, there were also several small boats on land.

Figure 17 -The Google Earth image above illustrates the area of Isla Cristina in Spain, over which the sixth spaceborne SAR image was acquired on 23 Dec. 2010.

3.1.8 – Coastal waters – Cascais Marina / Bay in Cascais-Portugal

The seventh and eighth SAR images were acquired over the area of the marina of Cascais near Lisbon in Portugal. Figure.18 illustrates the SAR images footprints of the SAR images acquired over the region of Cascais. The area was selected because it is representative of coastal waters and the availability of small boats that could be used as targets of opportunity. The spaceborne SAR images acquired over Cascais were a Radarsat2-Ultrafine and a TerraSAR-X Spotlight on 24 December 2010.

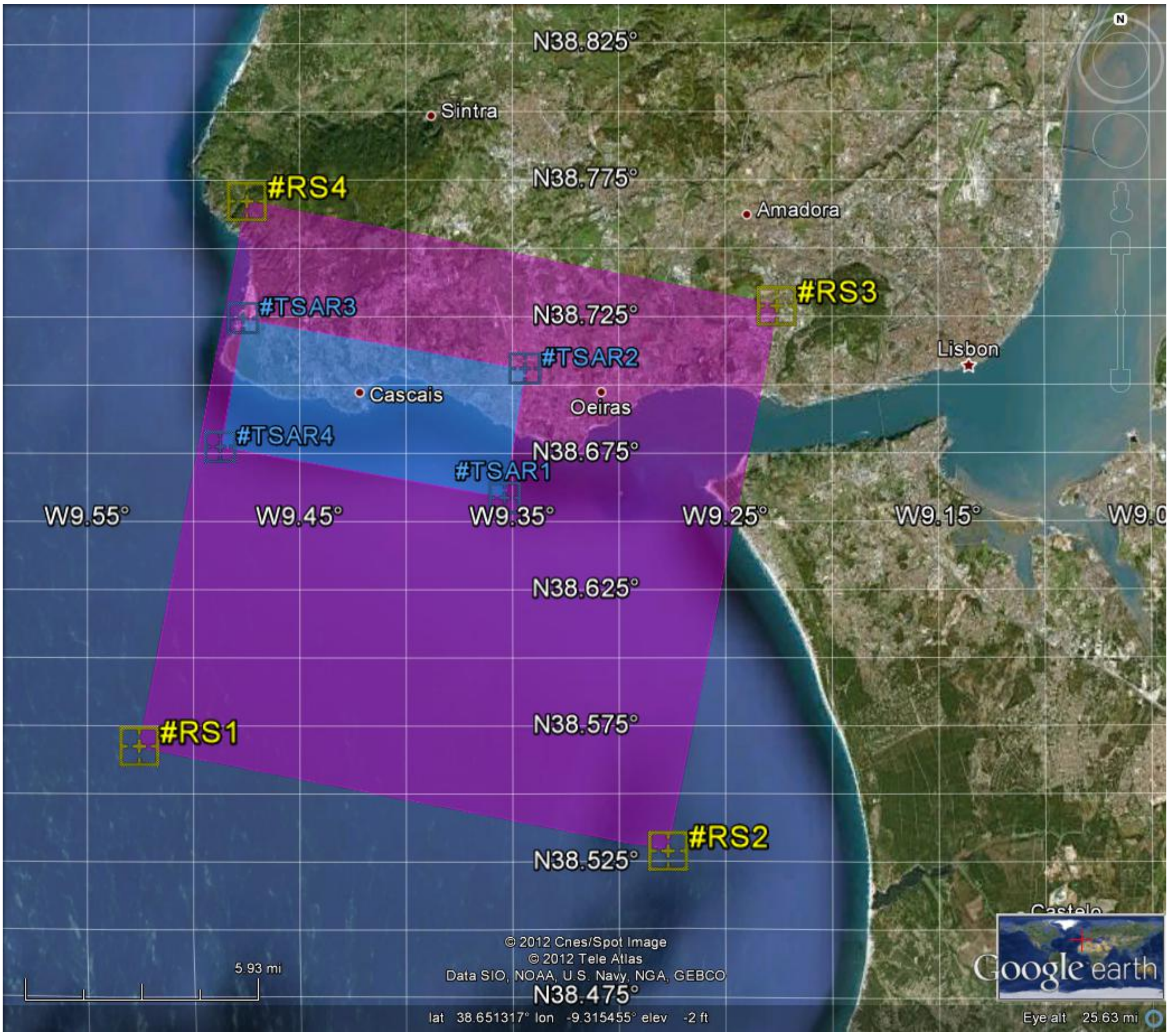


Figure 18 -The Google Earth image above illustrates the area of Cascais in Portugal, over which the seventh and eighth spaceborne SAR images were acquired on 24 Dec. 2010. The area in magenta is the footprint of the Radarsat2 Ultrafine image. The are in Blue is the footprint of the TerraSAR-X Spotlight image.

Figure.19, shows a significant number of small boats with sizes ranging from 3 to 10 meters between the Marina and the Bay of Cascais in Portugal. The small boats, used as targets of opportunity, were spread over the area between the Marina and the Bay of Cascais. Some of the small boats were moored to different piers. Most of the small boats were not packed or too close to each other, which is important to prevent SAR signature contamination. However, some of the boats were close to each other, mainly in the Marina. The area was selected because it is representative of coastal sea waters partially protected by the Marina and the availability of small boats spread over the area that could be used as targets of opportunity. Besides the small boats on sea water, there were also several small boats on land.

Figure 19 -The Google Earth image above shows the Bay and the Marina of Cascais in Portugal. Two SAR Satellite images were acquired over Cascais on 24 Dec. 2010, namely a Radarsat-2 Ultrafine and a TerraSAR-X Spotligh.

3.2 – Experiment Site Selection - Beach

The detection of small boats on land at the beach is also important. For example, illegal immigration by sea coming from the coast of Africa towards, Italy (Sardinia, Sicilia, Lampedusa, etc.), Spain (Canary Islands or the South of Spain) or from Turkey towards Greece usually involve a gathering of small boats at the beach several hours before the departure. If we could detect small boats on the beach using SAR satellite images, we could anticipate new waves of illegal immigrants and even prevent their departure by warning the authorities of the countries of origin. Any unusual gathering of small boats would trigger the alarm. The same is true for other illegal activities involving small boats, such as drugs trafficking and smuggling.

Although the main purpose of this controlled experiment was not the detection of small boats on land, in virtually all sites there were some small boats on land.

3.3 – SAR Satellite Imagery Planning

The Synthetic Aperture Radar (SAR) satellite imagery acquired in this experiment comprised Radarsat2 (Spotlight and Ultrafine) and TerraSAR-X (Spotlight). Table-2 summarises the SAR satellite Images and Modes acquired in the different days of the experiment. The SAR satellite images were acquired over Portugal and Spain.

The planning of all the SAR satellite images acquired during this campaign is illustrated in the sequence of figures given next (Fig.20 to Fig.35).

Table 2 – SAR satellite imagery acquired over Portugal and Spain.

PORTUGAL and SPAIN					
Date	**Time (UTC)**	**Area Selected**	**Satellite / Mode**	**Polarization**	**Pass**
13-Dec.-2010	18:24:04	Sancti Petri-La Barrosa-SP	Radarsat-2 / Spotlight	HH	ASC
14-Dec.-2010	06:39:24	El Rompido – Spain	Radarsat-2 / Spotlight	HH	DES
15-Dec.-2010	18:23:25	Sagres - Portugal	TerraSAR-X / Spotlight	HH	ASC
16-Dec.-2010	18:36:47	Punta Umbria – Spain	Radarsat-2 / Spotlight	HH	ASC
18-Dec.-2010	06:22:55	Cadiz – Spain	Radarsat-2 / Spotlight	HH	DES
23-Dec.-2010	18:32:38	Isla Cristina – Spain	Radarsat-2 / Spotlight	HH	ASC
24-Dec.-2010	06:46:40	Cascais - Portugal	TerraSAR-X / Spotlight	HH	DES
24-Dec.-2010	06:47:26	Cascais – Portugal	Radarsat-2 / Ultrafine	HH	DES

Figures 20 and 21 illustrate the planning for image: • Radarsat2-Spotlight, single polarization HH, Ascending pass, 13 December 2010 (Time-18:24:04), Sancti Petri-La Barrosa-Spain.

Figures 22 and 23 illustrate the planning for image: • Radarsat2 - Spotlight, single polarization HH, Descending pass, 14 December 2010 (Time-06:39:24), El Rompido – Spain.

Figures 24 and 25 illustrate the planning for image: • TerraSAR-X - Spotlight, single polarization HH, Ascending pass, 15 December 2010 (Time-18:23:25), Sagres - Portugal.

Figures 26 and 27 illustrate the planning for image: • Radarsat2 - Spotlight, single polarization HH, Ascending pass, 16 December 2010 (Time-18:36:47), Punta Umbria – Spain.

Figures 28 and 29 illustrate the planning for image: • Radarsat2 - Spotlight, single polarization HH, Descending pass, 18 December 2009 (Time-18:31:42), Cadiz – Spain.

Figures 30 and 31 illustrate the planning for image: • Radarsat2 - Spotlight, single polarization HH, Ascending pass, 23 December 2010 (Time-18:32:38), Isla Cristina – Spain.

Figures 32 and 33 illustrate the planning for image: • TerraSAR-X - Spotlight, single polarization HH, Descending pass, 24 December 2010 (Time-06:46:40), Cascais – Portugal.

Figures 34 and 35 illustrate the planning for image: • Radarsat2 - Ultrafine, single polarization HH, Descending pass, 24 December 2010 (Time-06:47:26), Cascais – Portugal.

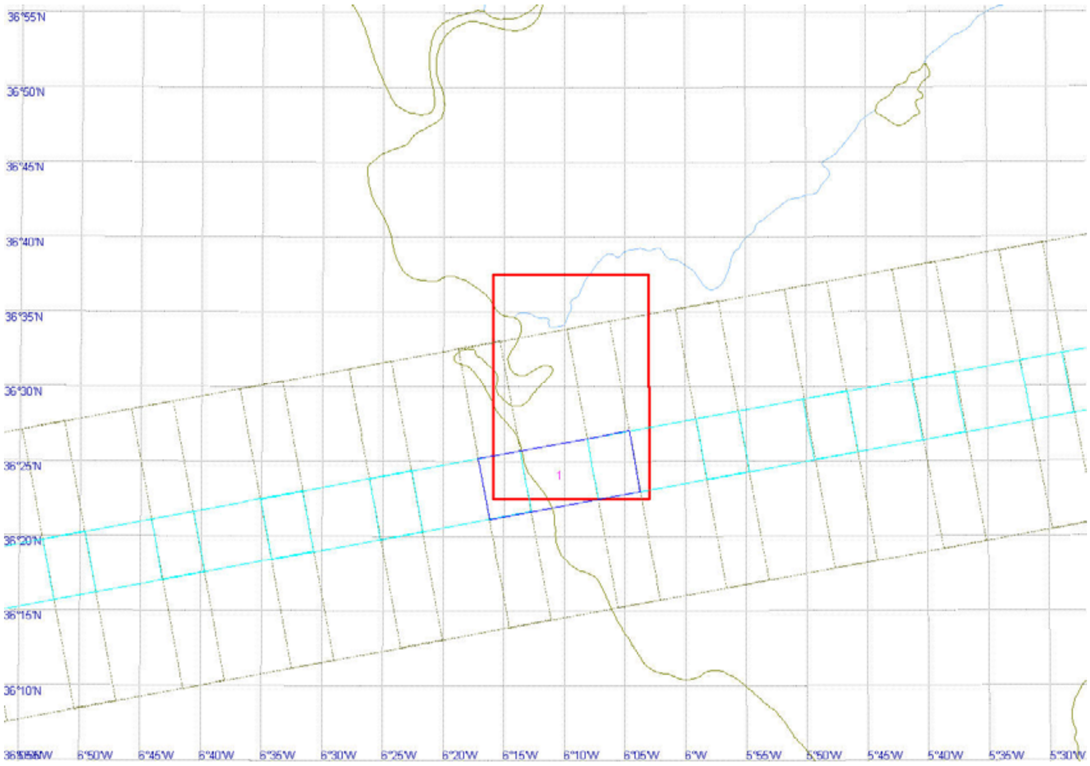


Figure 20 – Radarsat-2, Mode Spotlight, single polarization HH, Ascending pass, 13 December 2010 (Time-18:24:04), Sancti Petri-La Barrosa-Spain.

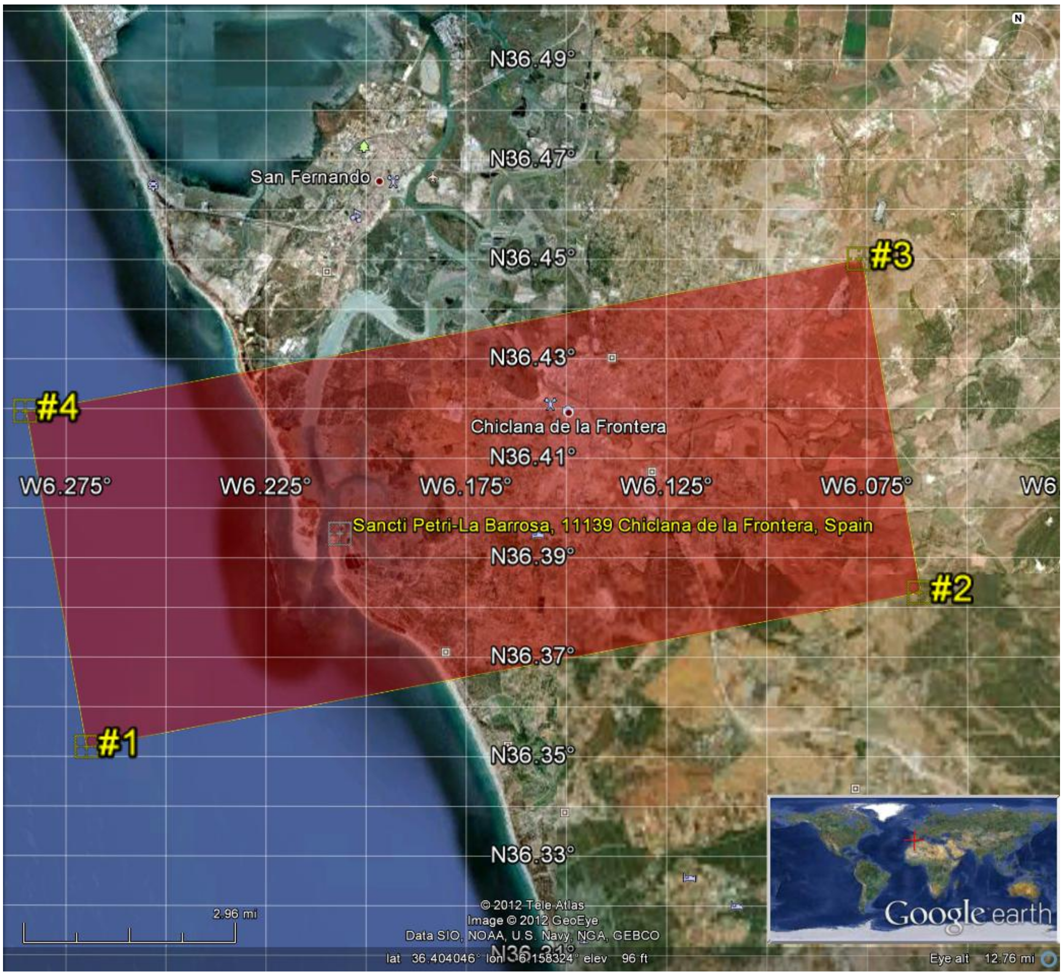


Figure 21 – Radarsat-2, Mode Spotlight, single polarization HH, Ascending pass, 13 December 2010 (Time-18:24:04), Sancti Petri-La Barrosa-Spain.

Figure 22 – Radarsat2 - Spotlight, single polarization HH, Descending pass, 14 December 2010 (Time-06:39:24), El Rompido – Spain.

Figure 23 – Radarsat2 - Spotlight, single polarization HH, Descending pass, 14 December 2010 (Time-06:39:24), El Rompido – Spain.

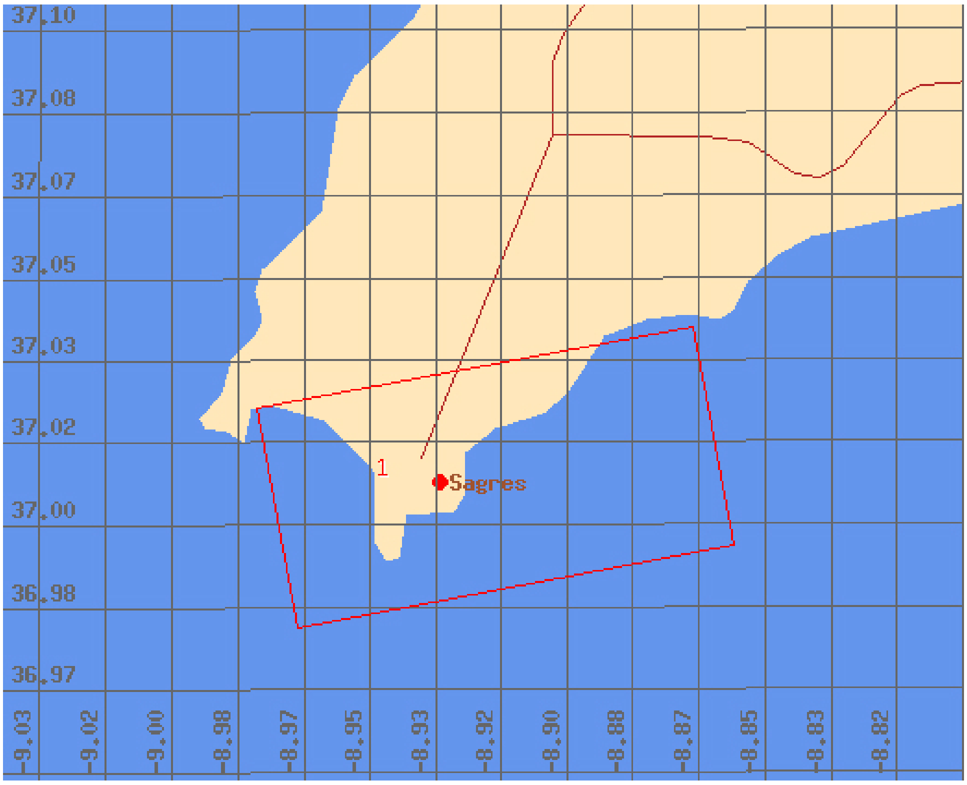


Figure 24 – TerraSAR-X - Spotlight, single polarization HH, Ascending pass, 15 December 2010 (Time-18:23:25), Sagres - Portugal.

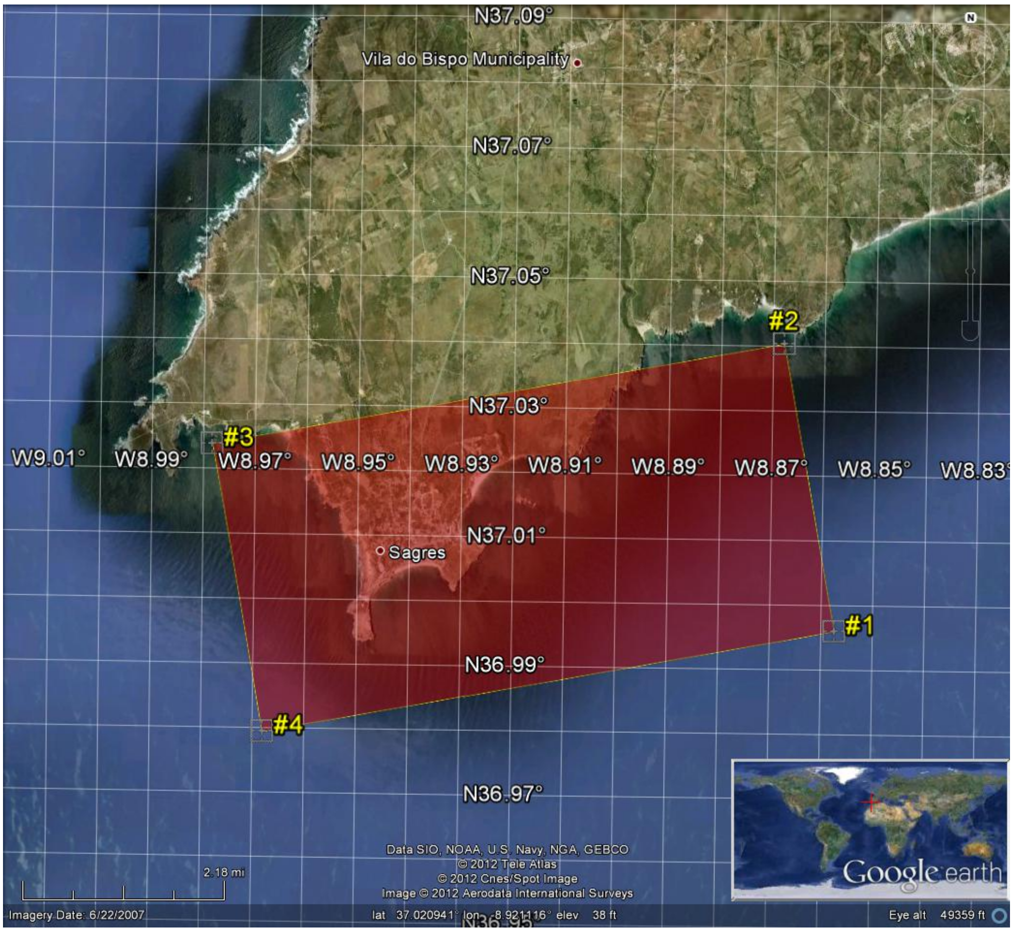


Figure 25 – TerraSAR-X - Spotlight, single polarization HH, Ascending pass, 15 December 2010 (Time-18:23:25), Sagres - Portugal.

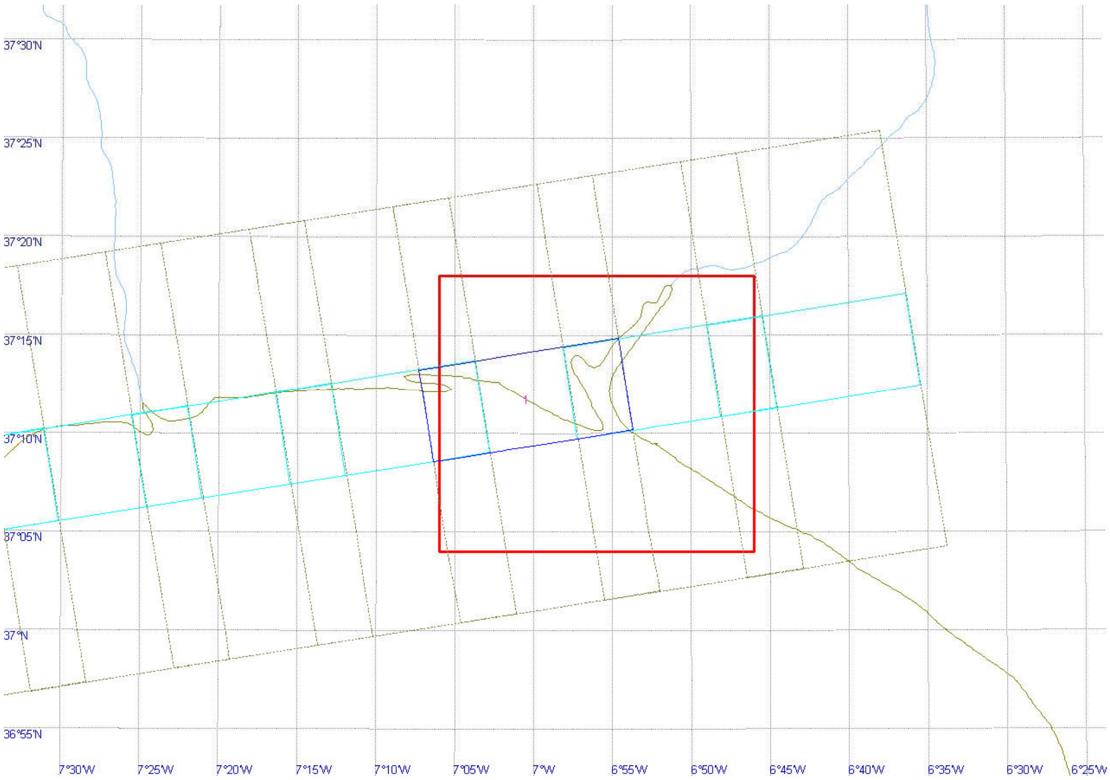


Figure 26 – Radarsat2 - Spotlight, single polarization HH, Ascending pass, 16 December 2010 (Time-18:36:47), Punta Umbria – Spain.

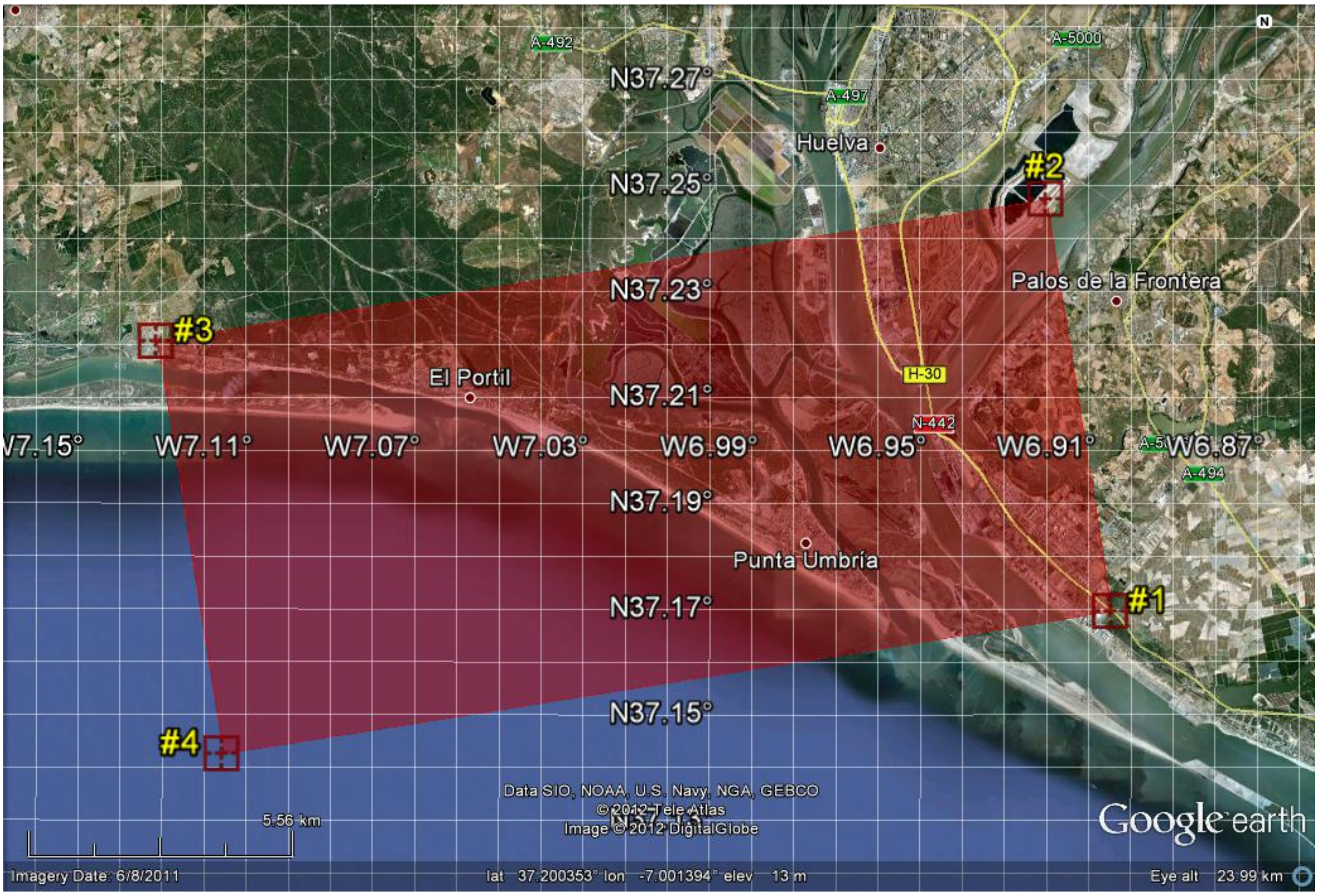


Figure 27 – Radarsat2 - Spotlight, single polarization HH, Ascending pass, 16 December 2010 (Time-18:36:47), Punta Umbria – Spain.

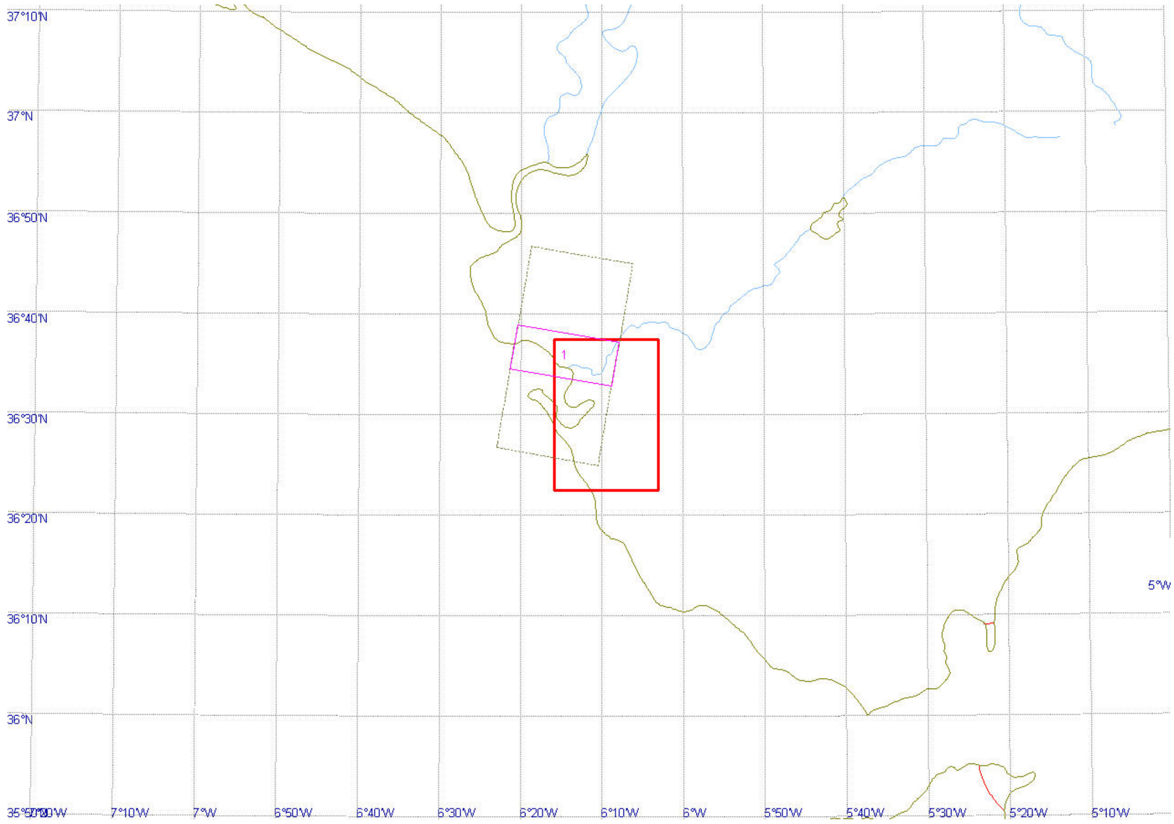


Figure 28 – Radarsat2 - Spotlight, single polarization HH, Descending pass, 18 December 2010 (Time-06:22:55), Cadiz – Spain.

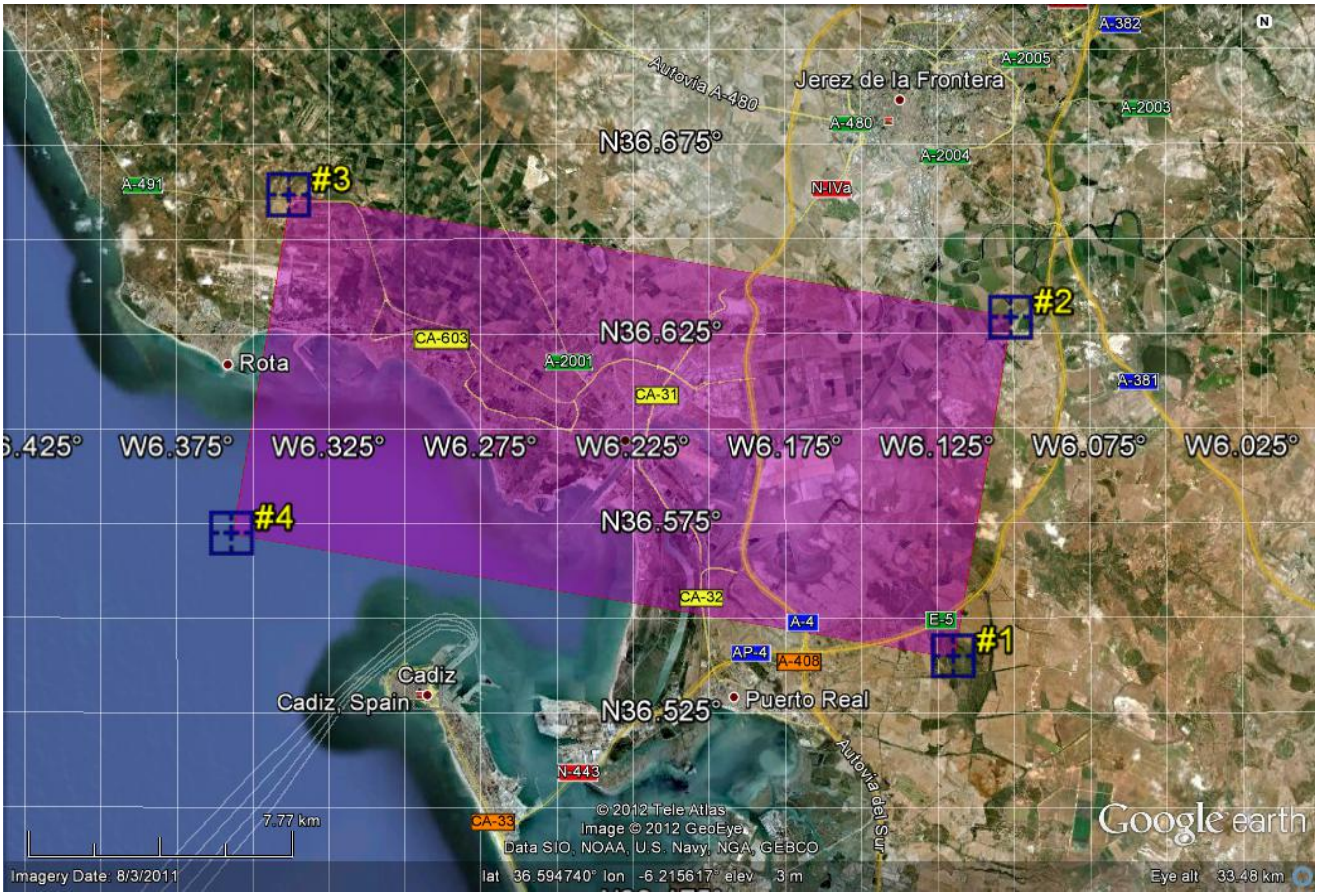


Figure 29 – Radarsat2 - Spotlight, single polarization HH, Descending pass, 18 December 2010 (Time-06:22:55), Cadiz – Spain.

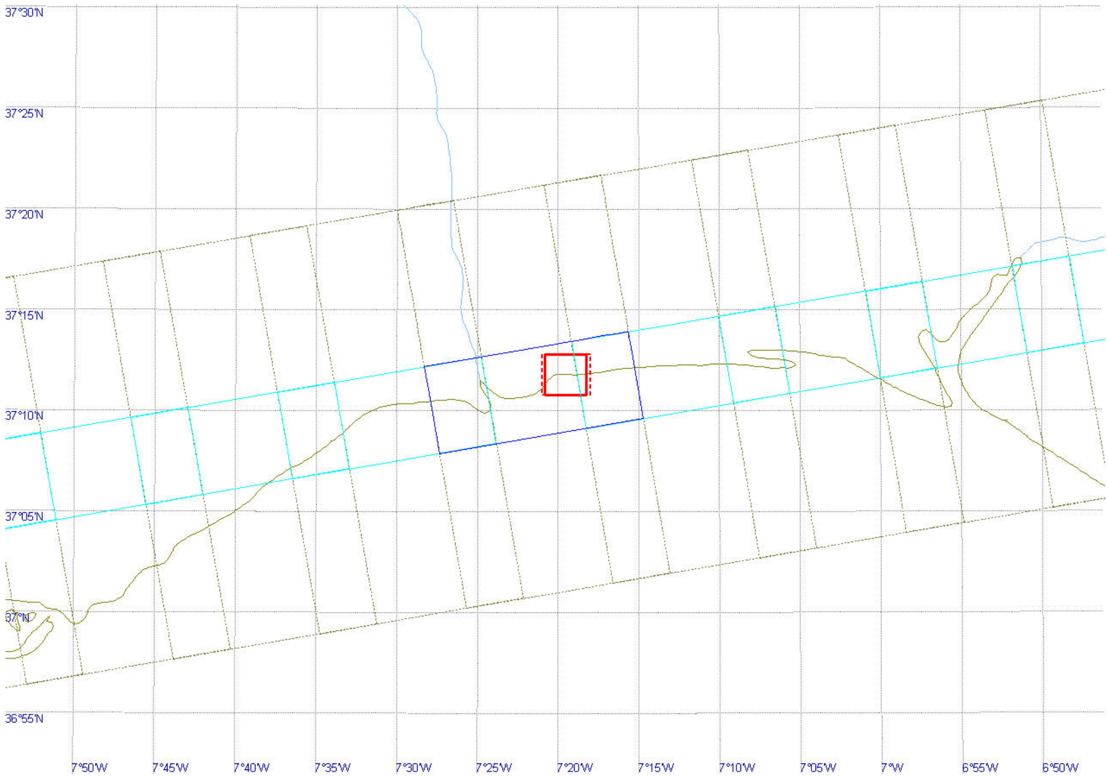


Figure 30 – Radarsat2 - Spotlight, single polarization HH, Ascending pass, 23 December 2010 (Time-18:32:38), Isla Cristina – Spain.

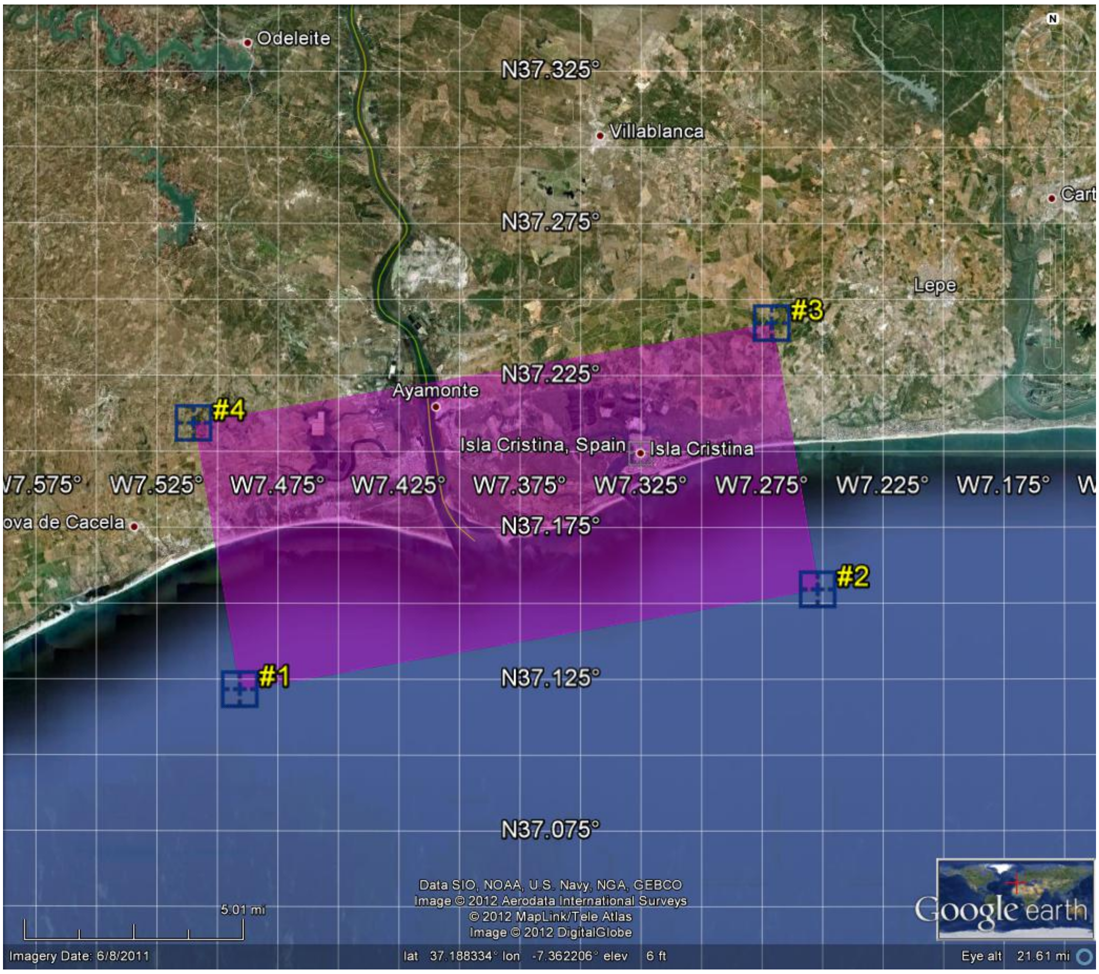


Figure 31 – Radarsat2 - Spotlight, single polarization HH, Ascending pass, 23 December 2010 (Time-18:32:38), Isla Cristina – Spain.

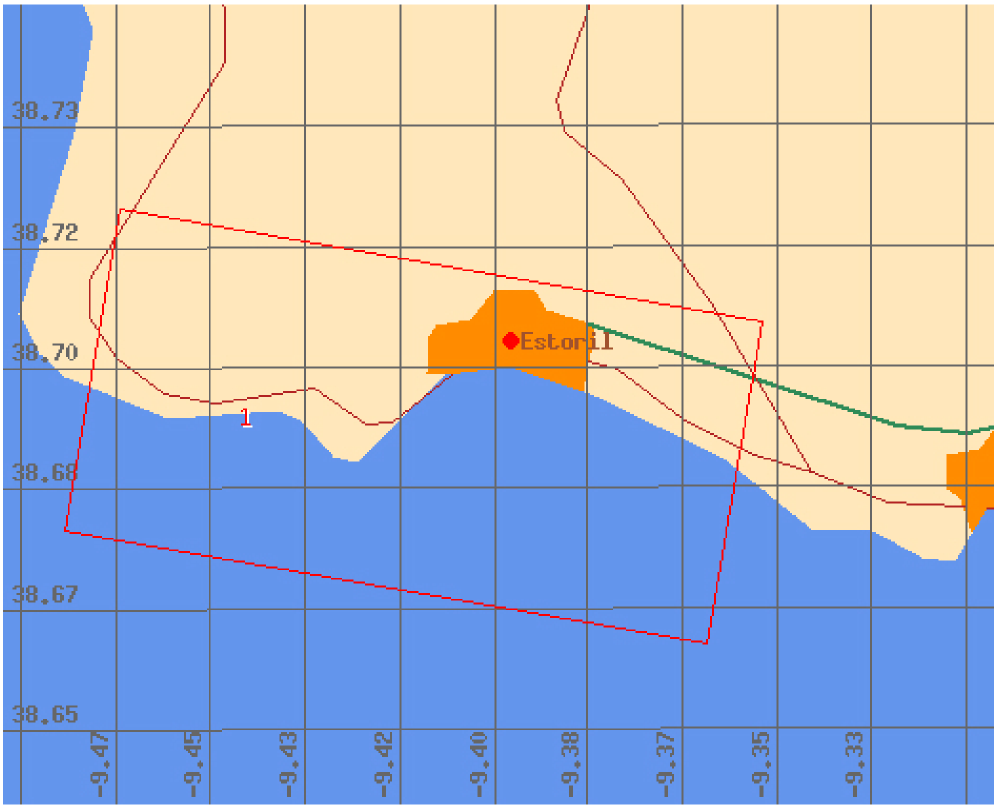


Figure 32 – TerraSAR-X - Spotlight, single polarization HH, Descending pass, 24 December 2010 (Time-06:46:40), Cascais – Portugal.

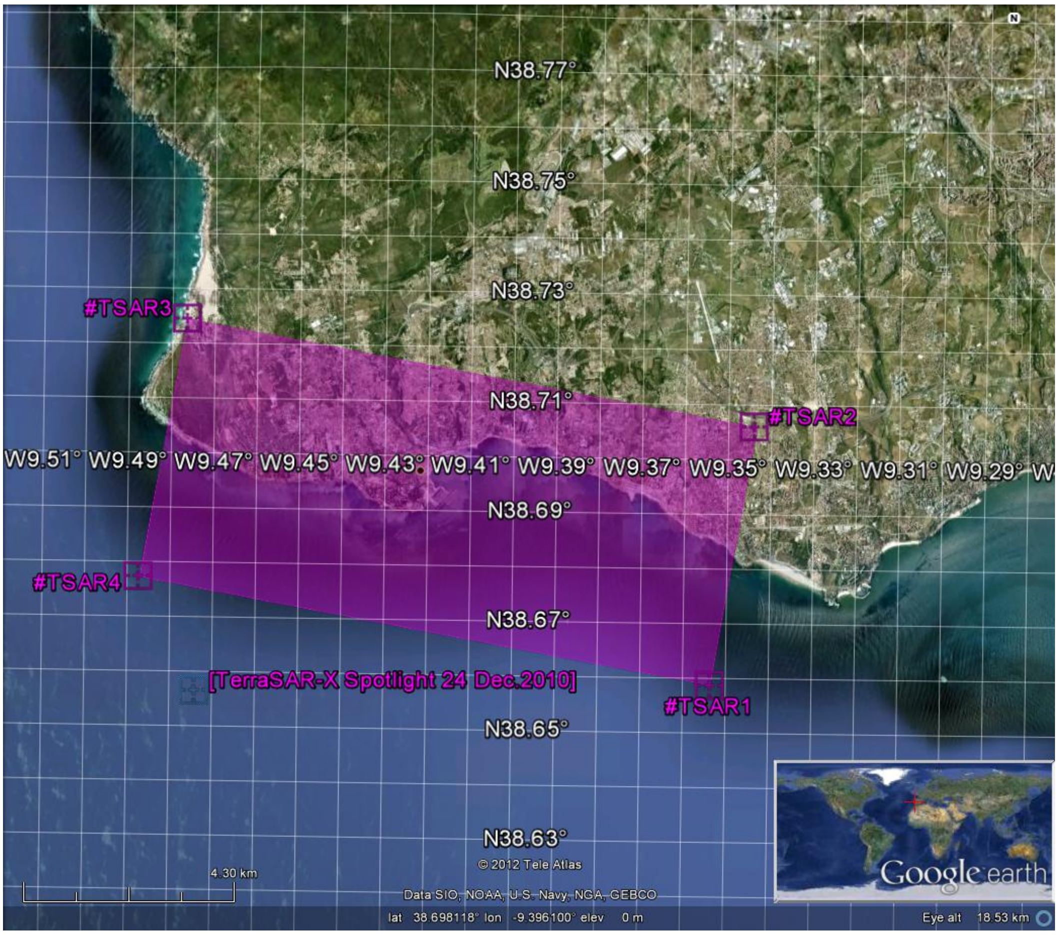


Figure 33 – TerraSAR-X - Spotlight, single polarization HH, Descending pass, 24 December 2010 (Time-06:46:40), Cascais – Portugal.

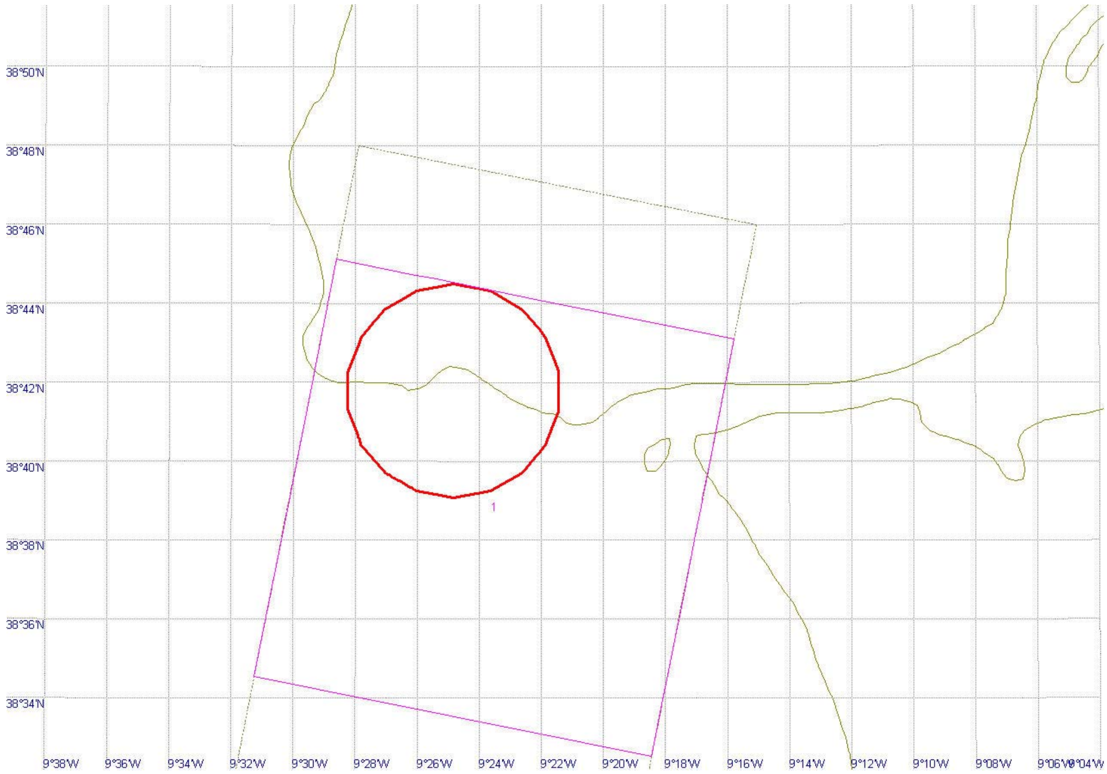


Figure 34 – Radarsat2 - Ultrafine, single polarization HH, Descending pass, 24 December 2010 (Time-06:47:26), Cascais – Portugal.

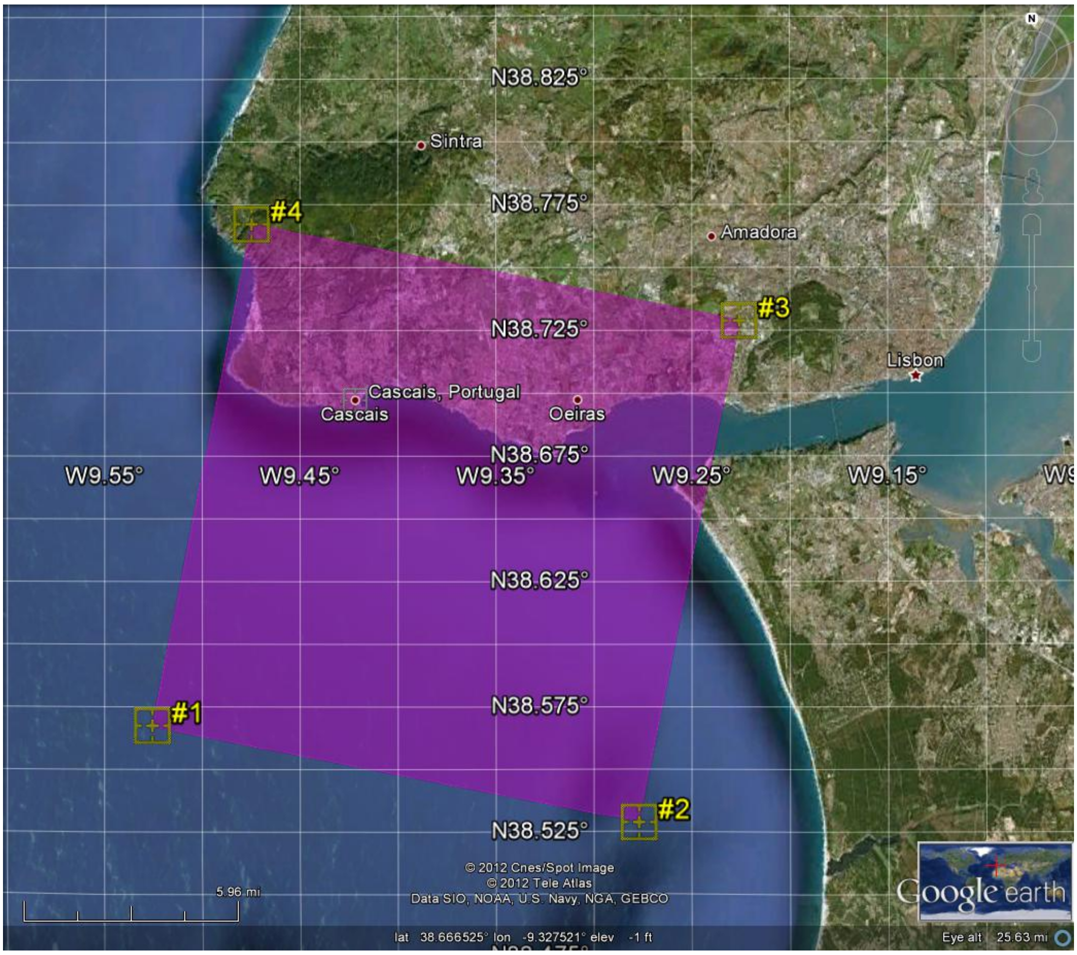


Figure 35 – Radarsat2 - Ultrafine, single polarization HH, Descending pass, 24 December 2010 (Time-06:47:26), Cascais – Portugal.

The Radarsat2 and TerraSAR-X image modes used in the present experiment will be briefly reviewed in the next paragraphs.

Radarsat2 - Spotlight Mode – The Spotlight Beams are intended for applications which require the best spatial resolution available from the RADARSAT-2 SAR system. In this mode the radar operates with the highest sampling rate, and so the ground swath coverage is limited to keep data rate within the recorder limits. Unlike the other modes, Spotlight images are also of fixed size in the along track direction.

The set of Spotlight Beams cover any area within the incidence angle range from 20 to 49 degrees. Each beam within the set images a swath width of at least 18 km. Spotlight images can only be generated in a single polarization, which can be either a linear co-polarization (HH or VV) or a linear cross-polarization (HV or VH).

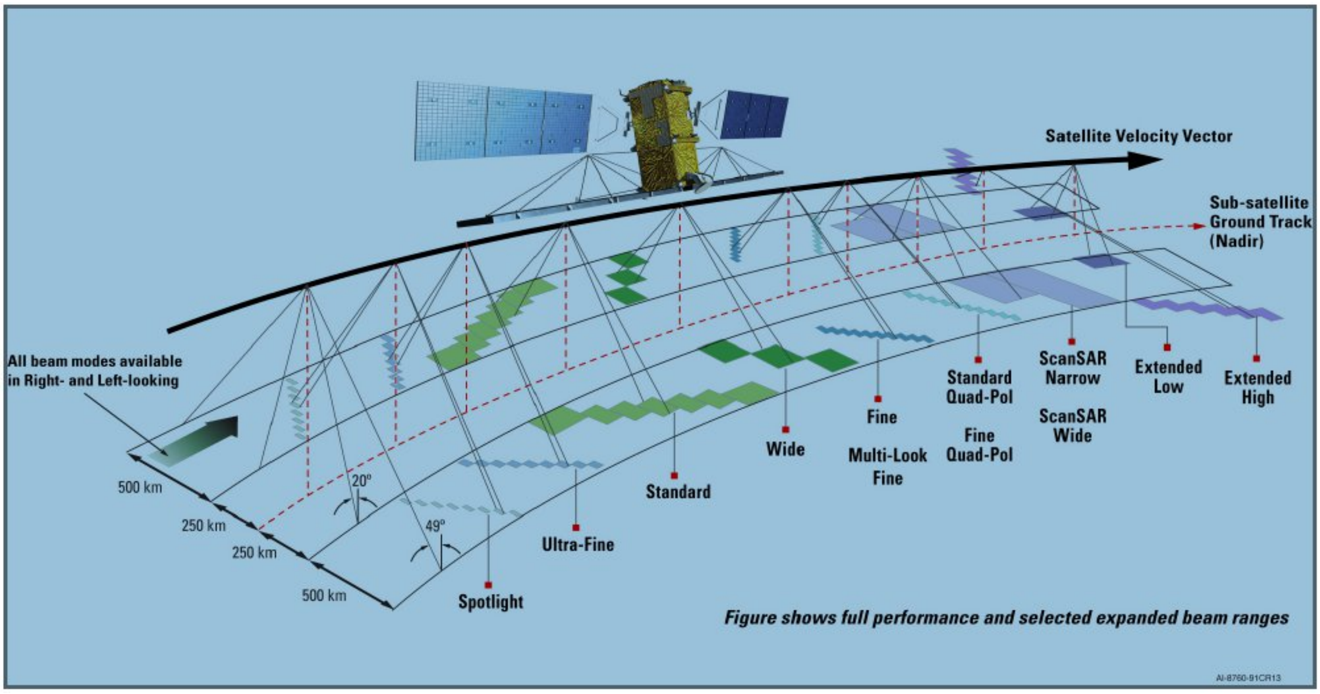


Figure 36 – Radarsart2 image modes. The Ultrafine and the Spotlight modes have been identified as the most suitable modes for this particular experiment © Copyright MacDonald, Dettwiller and Association (MDA) Ltd.2009.

Radarsat2 - Single Beam Mode – Single beam mode is a stripmap SAR mode. In Single Beam operation, the beam elevation and profile are maintained constant throughout the data collection period. The following Single Beam modes are available: Standard, Wide, Fine, Multi-Look Fine, Ultra-Fine, Extended High (High Incidence), Extended Low (Low Incidence), Standard Quad Polarization and Fine Quad Polarization. We selected Ultra-Fine because it is the best compromise between swath coverage and resolution.

Radarsat2 - Ultra-Fine – The Ultra-Fine Resolution Beams are intended for applications which require very high spatial resolution. In this mode the radar operates with the highest sampling rate, and so the ground swath coverage is limited to keep data rate within the incidence angle from 20 to 49 degrees. Each beam within the set images a swath width of at least 20 km. Ultra-Fine Resolution images can only be generated in a single cross-polarization , which can be either a linear co-polarization (HH or VV) or a linear cross-polarization (HV or VH).

The **standard TerraSAR-X operational mode** is the single receive antenna mode from which the following imaging modes can be retrieved: High Resolution Spotlight and Spotlight, StripMap, and ScanSAR. The single receive antenna mode uses a chirp
bandwidth of up to 300 MHz.

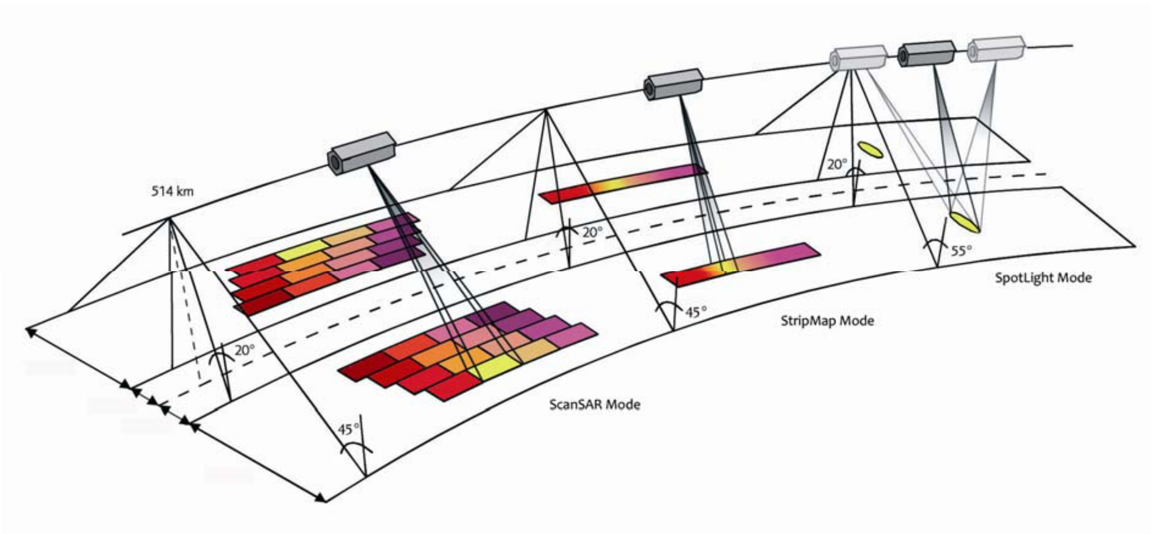


Figure 37 – TerraSAR-X image modes. The Spotlight mode has been identified as the most suitable mode for this particular experiment.

The **SpotLight (SL)** imaging modes use phased array beam steering in azimuth direction to increase the illumination time, i.e. the size of the synthetic aperture. This leads to a restriction in the image / scene size. Thus, the scene size is technically restricted to a defined size: 10 km x 10 km for the SpotLight mode and 10 km x 5 km (width x length) in the HighResolution SpotLight (HS) mode.

This sophisticated imaging mode makes it possible to acquire data with up to 1 m resolution in the HighResolution SpotLight mode (acquired with a bandwidth of 300 MHz) and 2 m in the standard SpotLight mode.

StripMap (SM) is the basic SAR imaging mode as known e.g. from ERS-1 and other radar satellites. The ground swath is illuminated with continuous sequence of pulses while the antenna beam is fixed in elevation and azimuth. This results in an image strip with a continuous image quality (in flight direction). StripMap dual polarisation data have a slightly lower spatial resolution and smaller swath than the single polarisation data.

In StripMap mode, a spatial resolution of up to 3 m can be achieved. The standard scene size is 30 km x 50 m (width x length) in order to obtain manageable image files; however, acquisition length is extendable up to 1,650 km.

3.4 – Partners Involved and their Roles

This experiment was carried out by the European Commission (EC)-Joint Research Centre (JRC), Institute for the Portection and Security of the Citizen (IPSC), Maritime Affairs Unit. The German Aerospace Centre (DLR) supplied TerraSAR-X Satellite imagery under proposal / grant agreement (OCE0633).

3.4.1 - European Commission (EC) – Joint Research Centre (JRC)

– The experiment was planned and conducted by the EC-JRC. This comprised:

a.) the definition of the objectives,
b.) the research methods used,
c.) the ground truth data collection,
d.) the analysis of the data and
e.) the conclusions of the experiment.

4. – Experiment Execution

4.1 – Inland Sea Waters - Modus Operandi

The modus operandi of the trial was as follows:

1.- JRC collected in-situ ground truth data and weather information in the area of the selected sites at the time of the satellite passes, namely:

a.) Photos of the targets of opportunity (small boats),
b.) Movies of the targets of opportunity (small boats),
c.) the sea state
d.) the wind speed
e.) the weather conditions

Since it was dark at the time of the satellite passes, ground truth information was also collected during daylight before or after the satellite passes for Ascending passes and Descending passes, respectively.

4.2 – Ground Truth Data Collection Limitations

The ideal ground truth data would comprise a flight over the area covered by the footprint of the satellite image during the satellite pass complemented by ground truth data collected on the ground. Unfortunately, a flight is very expensive and in this case, since at the time of the satellite passes it was dark, a flight would be useless. The only feasible ground truth data collection was on the ground before, during and after the satellite passes.

For Satellite Descending passes early in the morning (between 6:15AM and 6:45AM), the ground truth data was collected during the satellite pass using photos with flash and movies using camcorders with low light modes. This was followed by photos and movies at sunrise. The scenarios hardly change at this time in December.

For Satellite Ascending passes in the evening (between 18:15 and 18:45), the ground truth data was collected before the satellite pass during daylight and at the time of the satellite pass using photos with flash and movies using camcorders with low light modes. The scenarios hardly change at this time in December.

4.3 – Means Deployed

In this experiment, apart from digital cameras, camcorders and a GPS receiver, no other means were deployed. The main idea behind this experiment was to use targets of opportunity, namely small boats moored on Inland Sea Waters close by land.

5. – Preliminary Data Analysis

This section describes the analysis of the SAR Satellite images.

5.1 – SAR Satellite Imagery Processing

The high resolution SAR satellite images were analysed visually, since the resolution is good enough to allow visual analysis. The lower resolution SAR satellite images were also analysed visually because they cannot be processed using JRC vessel detection software, SUMO, due to the fact that the inland sea waters are surrounded by land, which causes masking problems and SAR signature contamination.

5.2 – Analysis of the SAR Satellite Imagery

The visual analysis of the SAR Satellite images was carried out with the following main objectives:

1. – To check if individual, targets of opportunity, namely small boats could be detected using SAR Satellite imagery, such as Radarsat2 Spotlight and Ultrafine and TerraSAR-X Spotlight.

2. – If possible, to estimate the empirical probability of small boat detection using SAR Satellite imagery, namely Radarsat2 Spotlight and Ultrafine and TerraSAR-X Spotlight.

3. – to understand the potential of using spaceborne SAR for small boat detection and to identify its main limiting factors.

The results of the analysis of the SAR Satellite images acquired during this experiment will now be described in turn, next.

5.2.1 – Radarsat2-Spotlight, 13 December 2010, Sancti Petri-La Barrosa-Spain.

The SAR Satellite image acquired over Sancti Petri-La Barrosa-Spain, was a Radarsat2-Spotlight, single polarization HH, Ascending pass, 13 December 2010 (Time-18:24:04). The frame (footprint) of the SAR image acquired covering Sancti Petri-La Barrosa is illustrated in Figure.38.

Sancti Petri-La Barrosa in Spain was the first location selected for the experiment. The area was selected due to the inland sea waters and the availability of small boats that could be used as targets of opportunity.

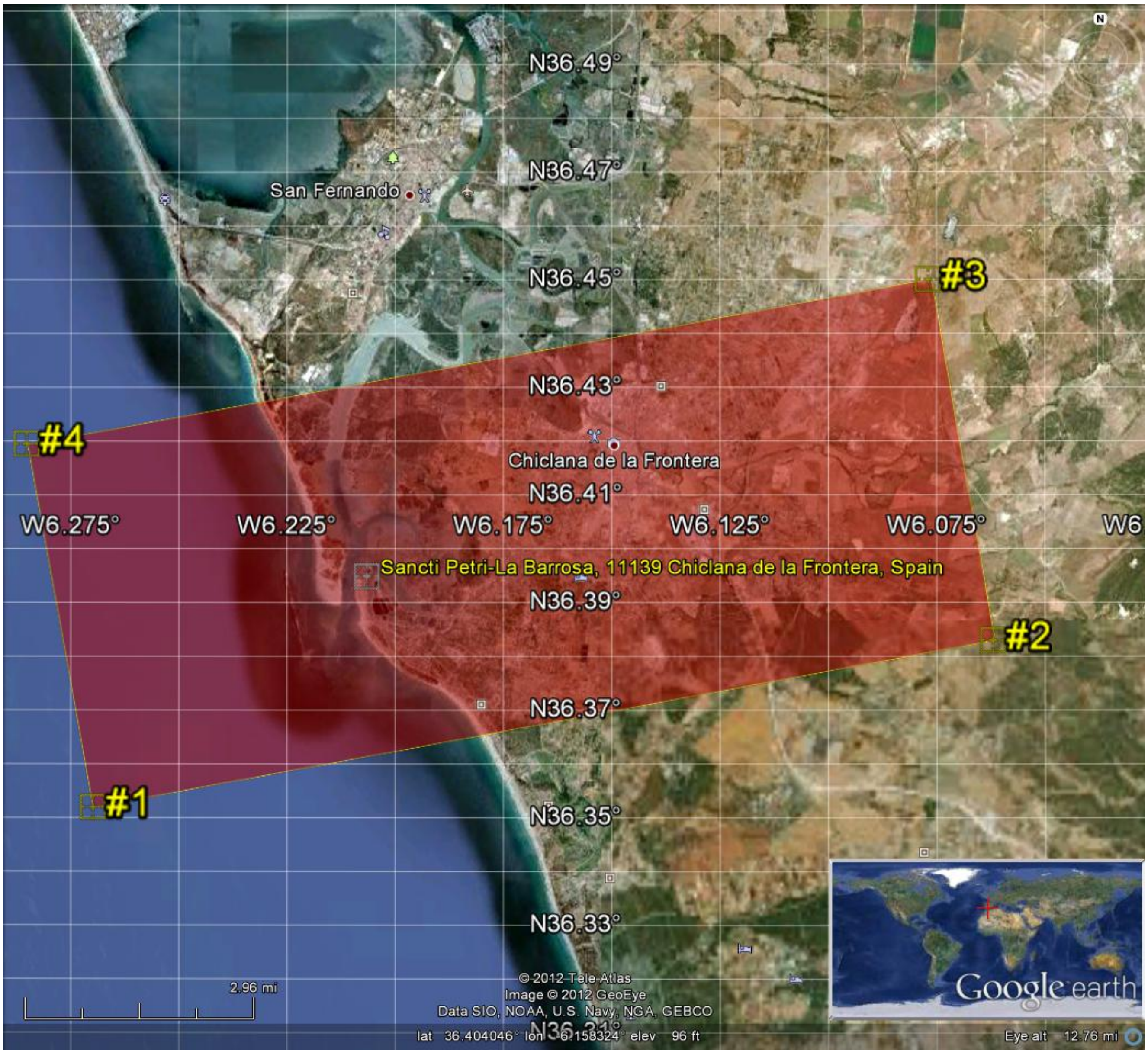


Figure 38 – Footprint of the Radarsat2-Spotlight image acquired over Sancti Petri-La Barrosa-Spain on 13 Dec. 2010 by 18:24h.

The SAR image was calibrated using NEST, an ESA software package. An overview of the Sancti Petri-La Barrosa area in the Radarsat2-Spotlight image is given in Figure 39. As it can be seen, there are several targets of opportunity detected. Most small boats moored on sea not too close to other targets were detected. Some of the bright spots in the image correspond to sets of small boats too close to each other. There was SAR signature contamination. The small boats moored to piers also have contaminated SAR signatures by the backscattering from other nearby boats and the piers.

Figure 39 shows an overview of the entire target area covered by the Radarsat2-Spotlight divided into four zones to facilitate the comparison of the SAR image with the ground truth. Zone 1 in yellow shows some small boats spread. Some of the boats are on land and the remaining on water. Zone 2 in magenta shows small boats more packed than in zone 1, again, some of the boats are on land and the remaining boats on sea. Zone 3 green is the zone located East of the first pier. Zone 2 in blue is the zone covering the first pier. Zone 3 in green shows a large number of small boats. Most of the boats are spread along the Marina and a smaller number that are moored to the piers of the Marina are packed. Finally, zone 4 in blue covers the area between the second and the third piers. Zone 4 in blue shows a significant number of small boats spread on sea.

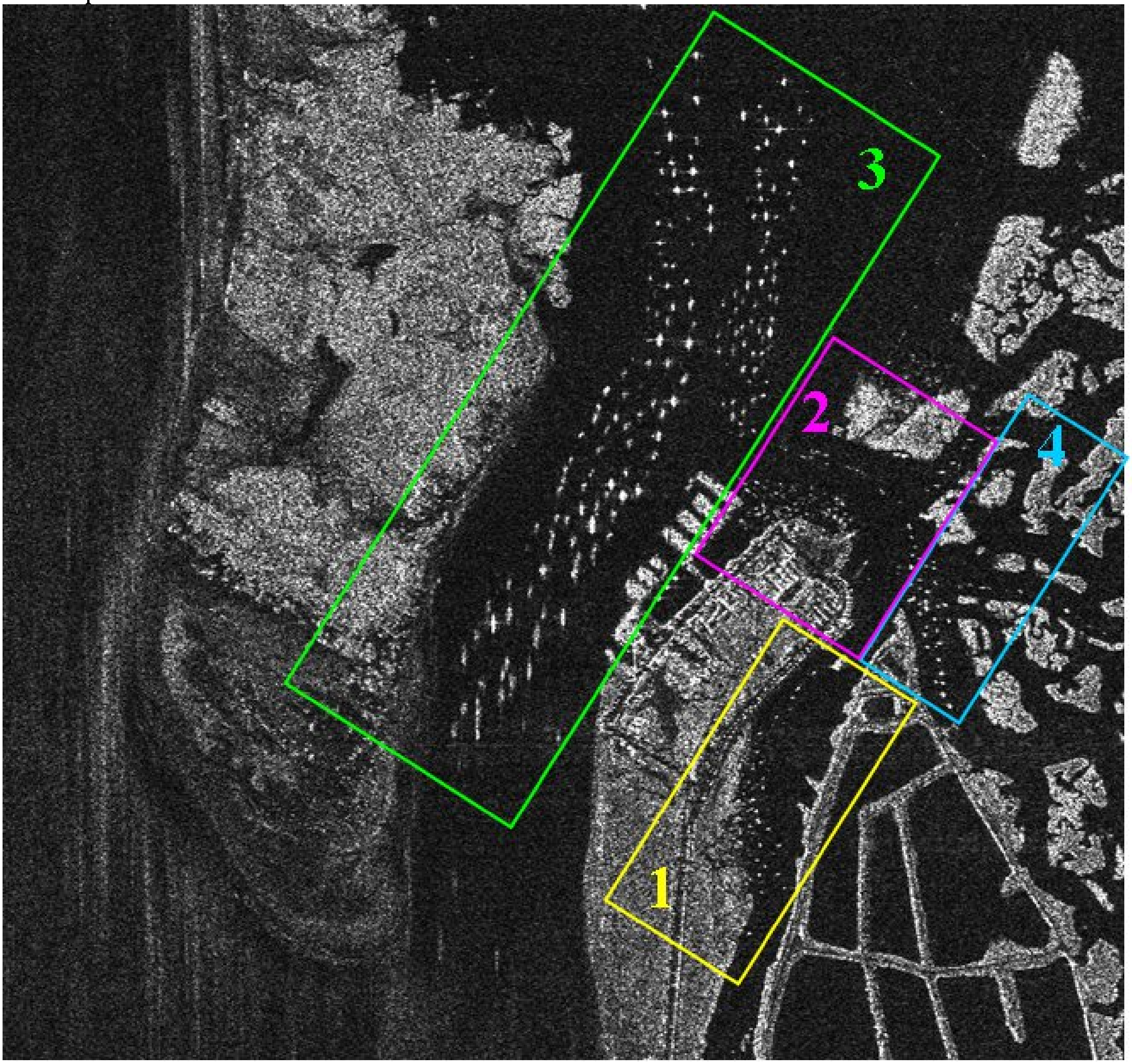


Figure 39 – Radarsat2-Spotlight image, 13 Dec. 2010, by 18:24h UTC. The image was divided into 5 zones to facilitate the analysis and comparison with the ground truth data.

A first analysis of the SAR image shows a large number of small targets detected. In order to facilitate the analysis, the SAR image was divided in four main zones illustrated in figure 39. Before comparing the SAR image with the ground truth data, it is interesting to compare the SAR image with the corresponding optical image from Google–earth in figure 40. It should be noted that the optical image from Google-earth cannot be used as a replacement of the ground truth data because it was acquired at a different date and time. However, it is interesting to see that the patterns defined by the small targets detected in the SAR image are similar to the patterns defined by the small boats in the optical image from Google-earth. Although the small boats and their respective positions are not the same in the two images, the type and number of small boats detected in both images exhibit some similarities.

An interesting particularity to notice is the detection of a couple of shipwrecks in the SAR image, which were already in their actual positions when the optical image from Google-earth was acquired. There are at least two cases of such shipwrecks in zone 2, which will be addressed with the analysis of zone 2.

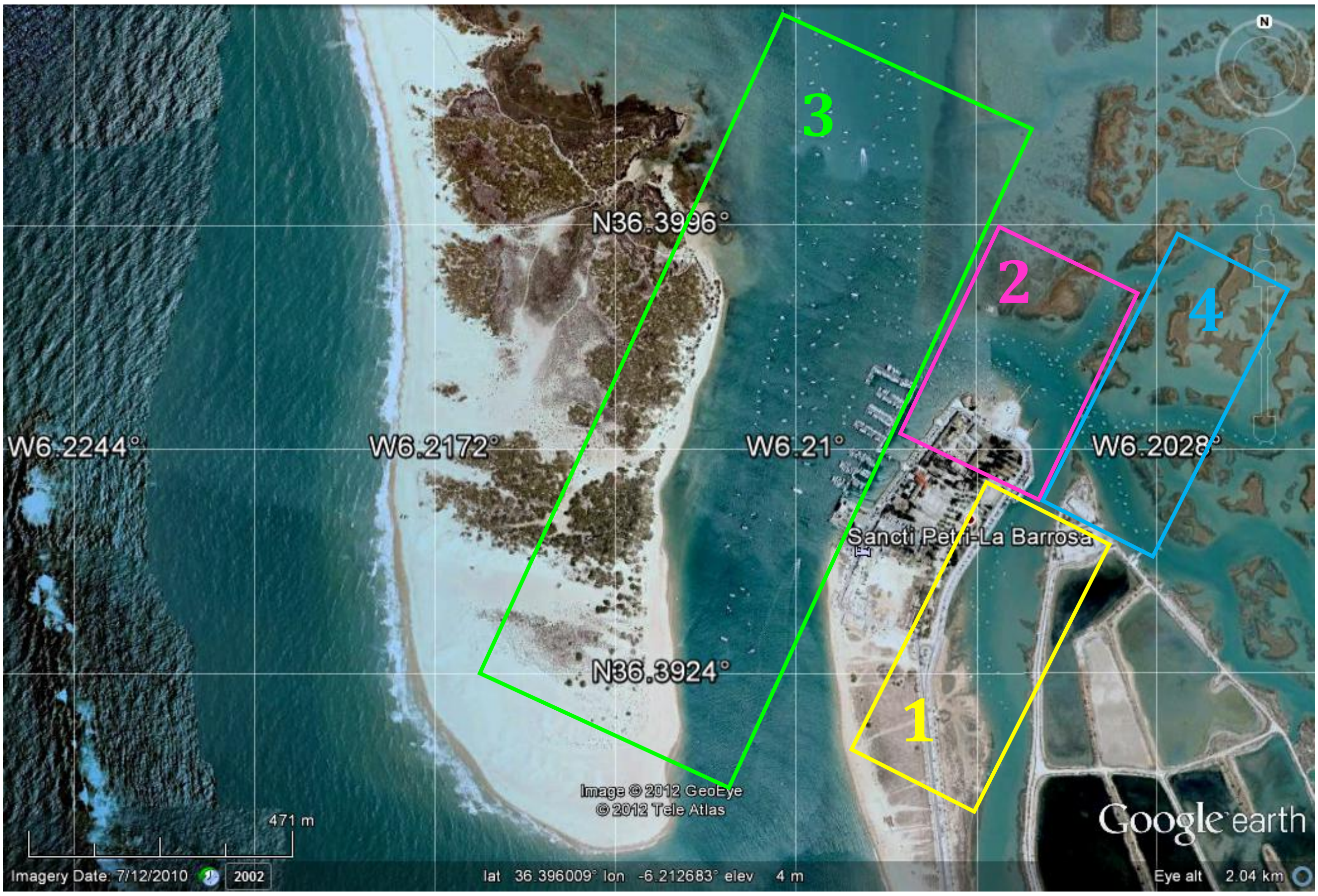


Figure 40 – Google-earth optical image of the area of Sancti Petri-La Barrosa.

The SAR image acquired on 13 December 2010 over Sancti Petri-La Barrosa-Spain will be addressed next. The analysis will be performed by zones 1 to 4, each in turn.

 Zone 1

– Comparing figures 39 (SAR image) and 40 (Optical image) it can be seen that a significant number of small boats detected in the SAR image are on land and the remaining small boats are in water. It is not easy to count the number of boats detected on land due to the electromagnetic radiation backscattered from the background. The ground truth data includes the GPS position of virtually all small boats on land. Counting the number of small boats detected in the SAR image and dividing that number by the total number of small boats obtained from ground truth data, an empirical estimate of the probability of detection can be calculated. It should be noted that this probability is not more than a rough estimate of the percentage of small boats detected using the same SAR sensor under the same circumstances. It cannot be generalised to any other experiment with different characteristics.

– Figure 41 shows the identification of small boats detected in the Radarsat-2 Spotlight image in zone 1, base on the ground truth data collected in-situ. Virtually all small boats in water were detected. Since this is an area of inland waters, the sea state does not affect significantly the SAR signatures. The SAR signatures do not show evidence of significant motion effect. Smearing, when present is virtually negligible. The analysis of zone 1 shows that under suitable conditions of sea state and wind speed, SAR spaceborne can be used to detect small boats. In the present case the sizes of the small boats detected in most cases range from 3 to 6m. Concerning the small boats on land, the ground truth data confirmed that most of the small boats on land were also detected. However, the contrast between their SAR signatures and the backscattering of the land background is very low. Hence, the identification of their SAR signatures is not straightforward.

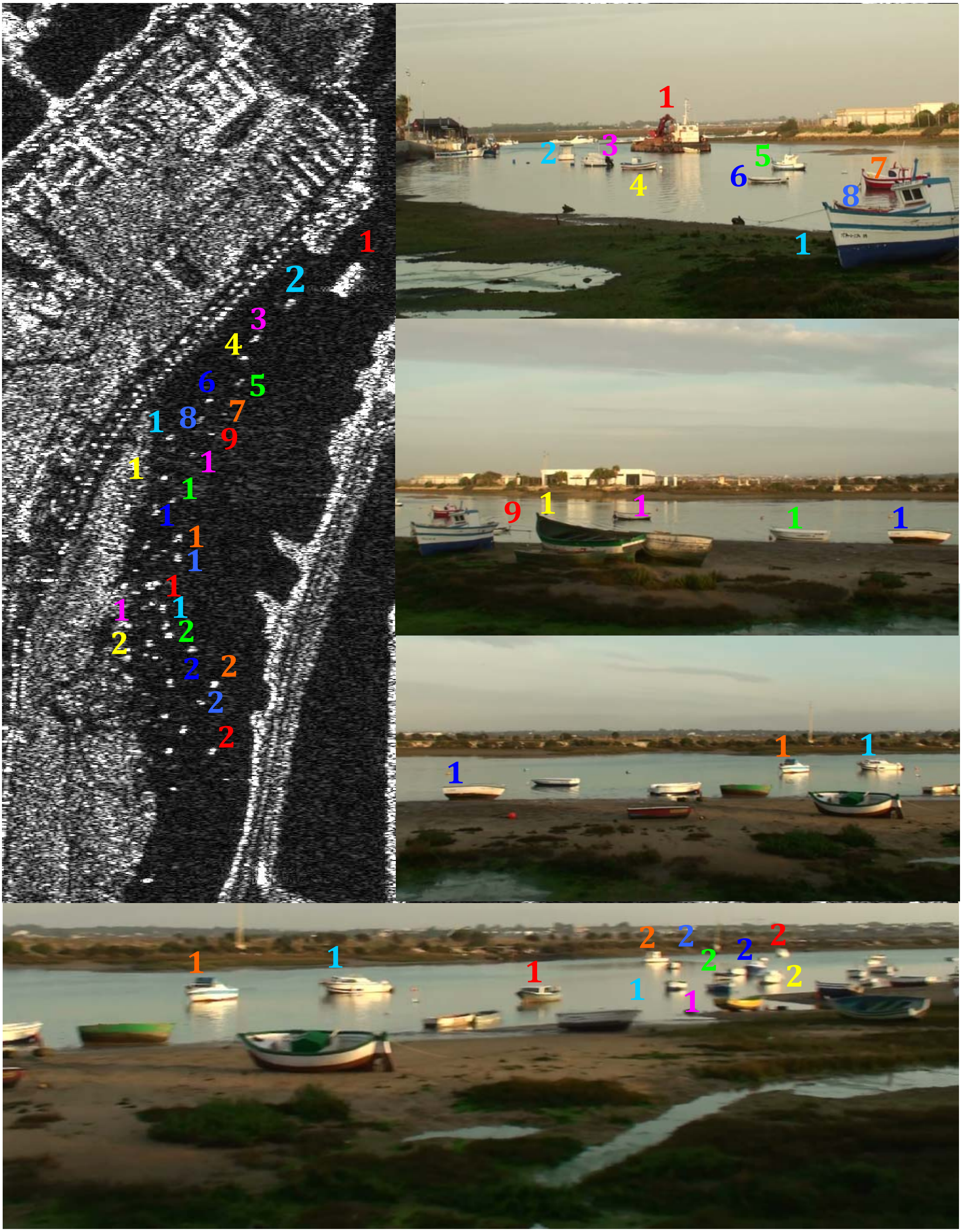


Figure 41– Identification of detected Small Boats in zone 1 based on ground truth data collected in-situ.

Zone 2

A preliminary analysis of zone 2 shows a significant number of small boats detected. Like in zone 1, some of the boats are on land and most boats are in the water. Zone 2 is slightly more exposed to changes on sea state than zone 1. However, in the present case the SAR signatures of the small boats in zone 2 do not show additional smearing when compared to zone 1. Visually they are similar.

Figure 42 shows a subset of the SAR image, corresponding to part of Zone 2 on the left and the corresponding Google-earth image on the right. The Google-earth image is shown just to identify 2 piers and the size of two 20m long shipwrecks which are present on both images. The two shipwrecks provide a good scale reference. Knowing that the approximate sizes of the shipwrecks are about 20m, comparing the SAR signatures of the shipwrecks with the SAR signatures of the small boats a rough estimation of the size of the small boats can be made. Based on the ground truth data and the above mentioned shipwrecks the average size of the small boats is smaller than 10m.

It should be noted that the small boats on the Google-earth image are not the same as the ones on the SAR image. The Google-earth image was created long before the SAR image. However, the type and size of the small boats is approximately the same. In some cases some of the small boats on the Google-earth image might also be on the SAR image, but in a different position because the two images were created at different times. The two images are supplied side by side to facilitate the identification of the piers and mainly to show the two shipwrecks, which are the same in the two images and can be used as a reference.

Figure 43 shows a few more small boats detected in zone 2 of the SAR image.

Zone 3

Figure 44 shows a panoramic view of the area covered by zone 3. It is the area with the largest number of boats. It can be characterized by the local Marina and a large number of small boats of different types (e.g. recreational, sailboats and fishing vessels) and sizes e.g from 3 to 15m. Sailboats can be easily identified due to the smearing effect caused by the motion of their masts. The boats moored to the Marina are packed. The remaining boats are spread.

Figure 45 illustrates the identification of the SAR signatures for some boats based on the ground truth data collected in-situ at the time of the satellite pass.

Zone 4

Zone 4 can be characterized for a small number of small boats spread in the water. The sea state effect in zone 4 is negligible when compared to zones 2 and 3 because zone 4 is not as exposed as zones 2 and 3. Figure 46 shows that virtually all small boats in zone 4 were detected.

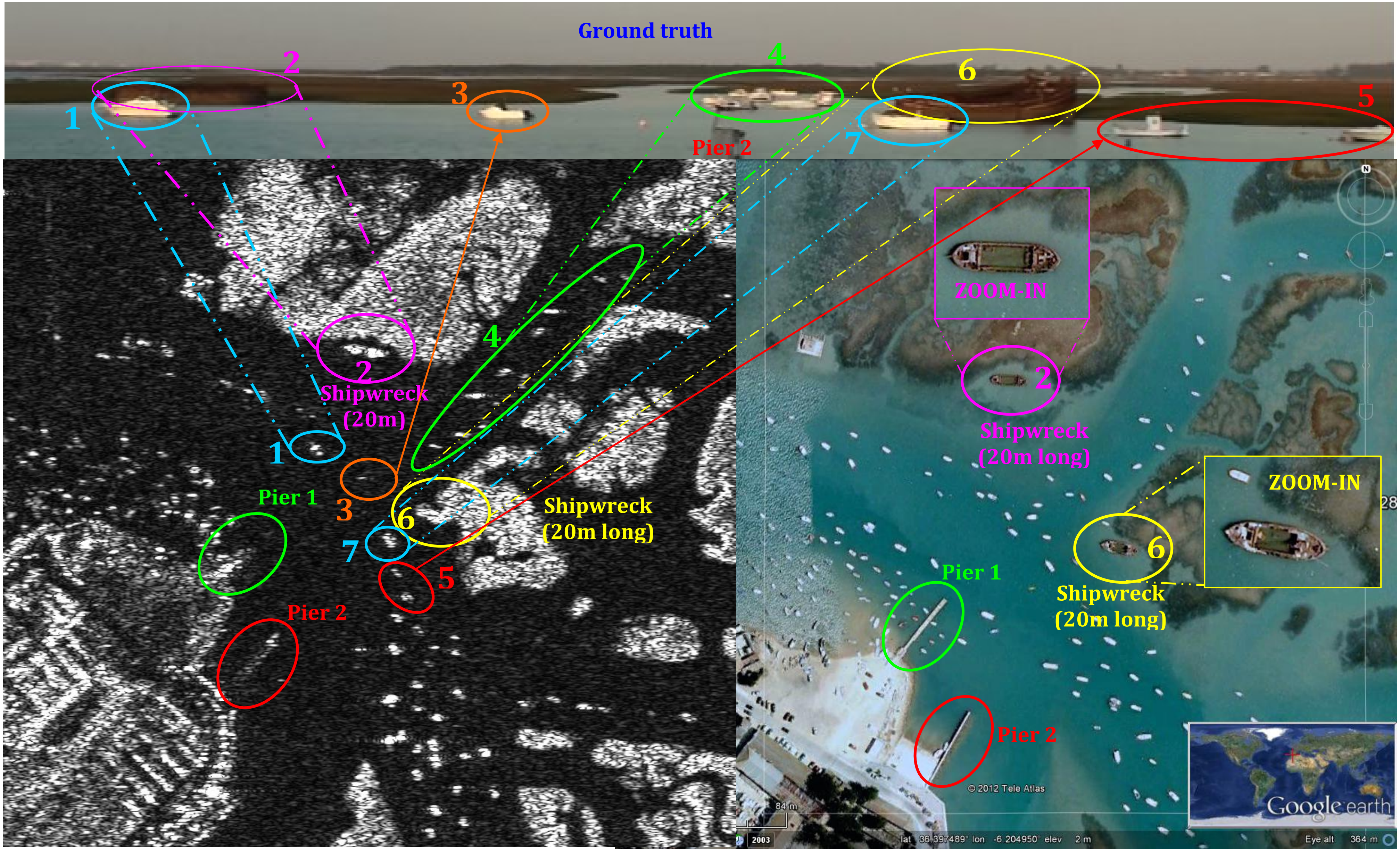


Figure 42 – On the left subset of the SAR image (zone 2). On the right the corresponding Google-earth image. It should be noted that the two images were created at different dates and times, therefore the SAR signatures of small boats on the left do not correspond to the small boats seen on the optical image on the right.

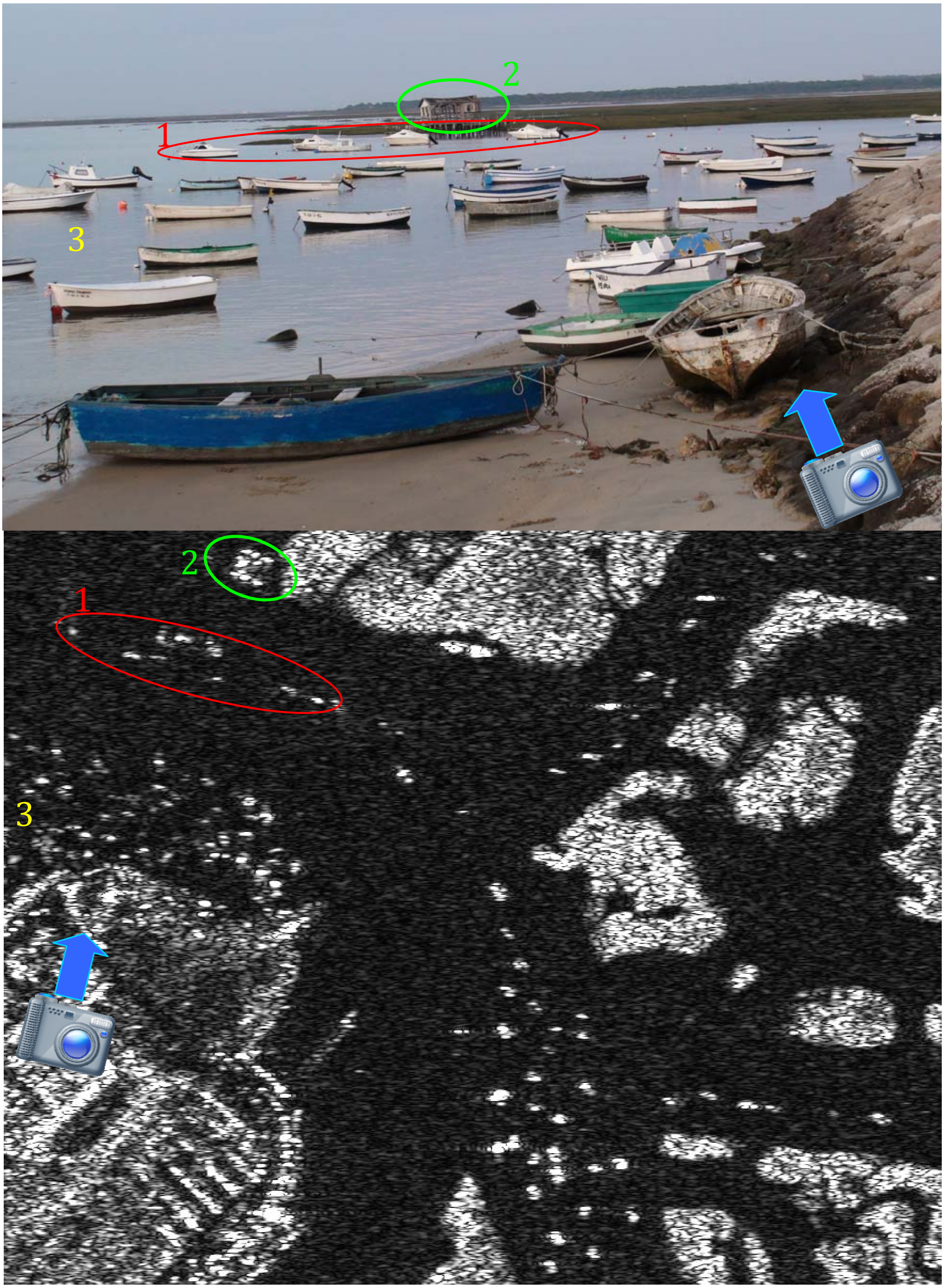


Figure 43– Small boats detected in the SAR image, zone 2. The area (1) in red shows 5 small boats detected. The area (2) in green shows a wooden made house. The area (3) in yellow represents a set of small boats.

Figure 44 – Panoramic view of zone 3. The photo was taken from the Marina of Sancti Petri-La Barrosa in Spain. Small boats detected in the SAR image, zone 2. The area (1) in red shows 5 small boats detected. Target (1) in red is a cargo ship. On the right hand side the Marina. In the middle a large number of small boats spread along and beyond the Marina.

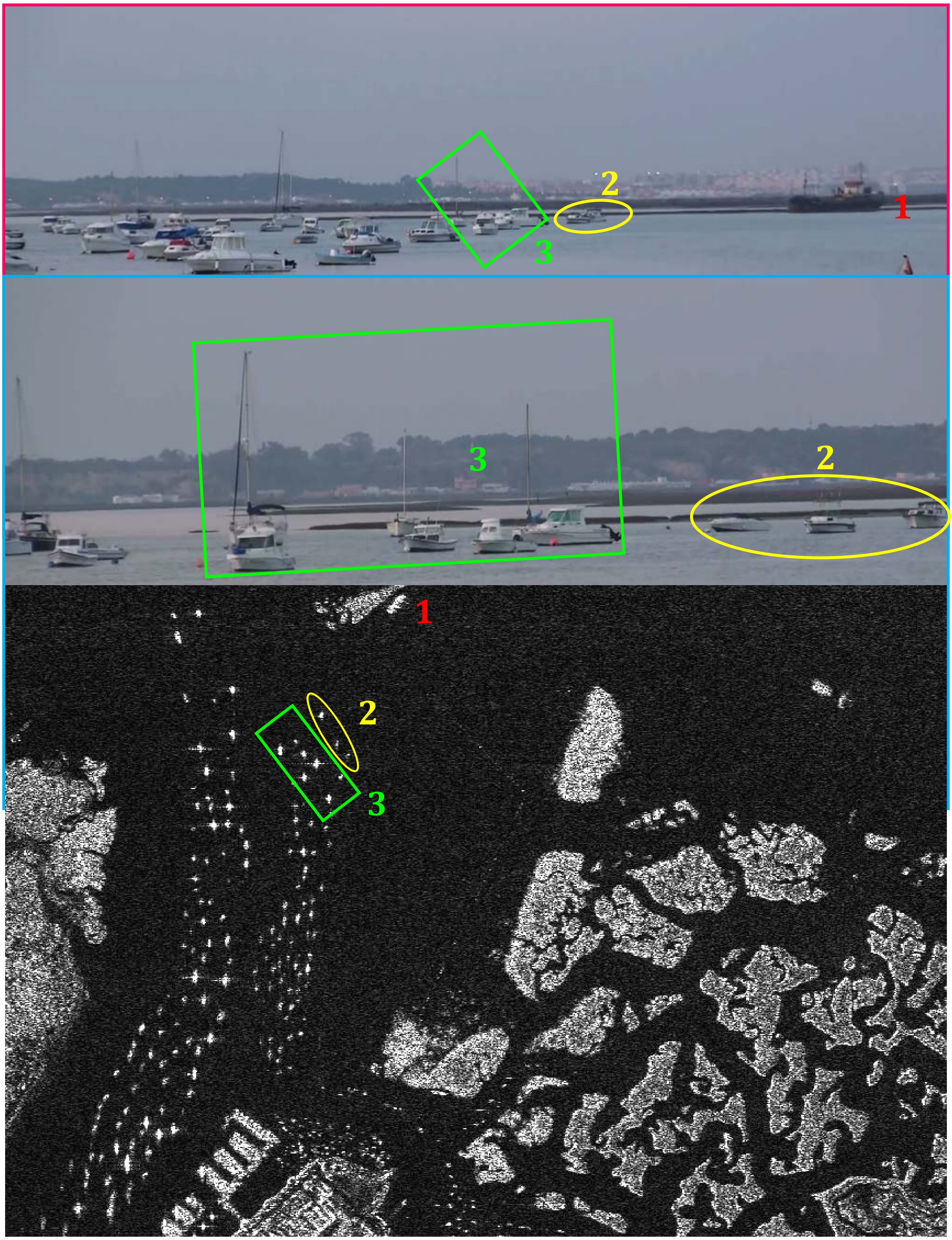


Figure 45 – On the top, two photos of Sancti Petri-La Barrosa in Spain, taken at the time of the satellite pass. On the bottom a subset of the corresponding SAR image. The SAR image shows a large number of small boats detected in zone 3. Target (1) in red is a cargo ship. Area (2) in yellow includes 3 small boats (3-6m). Area 3 in green shows 7 boats, 3 of which are sailboats, as it can be seen by the smearing effect caused by the motion of their masts.

The last zone of the SAR image analysed (zone 4) is characterised by two main sets of small boats in the water. The zone 4 is more protected than zones 2 and 3, but more exposed to changes in sea state than zone 1. Figure 46 shows that virtually all small boats were detected in the SAR image.

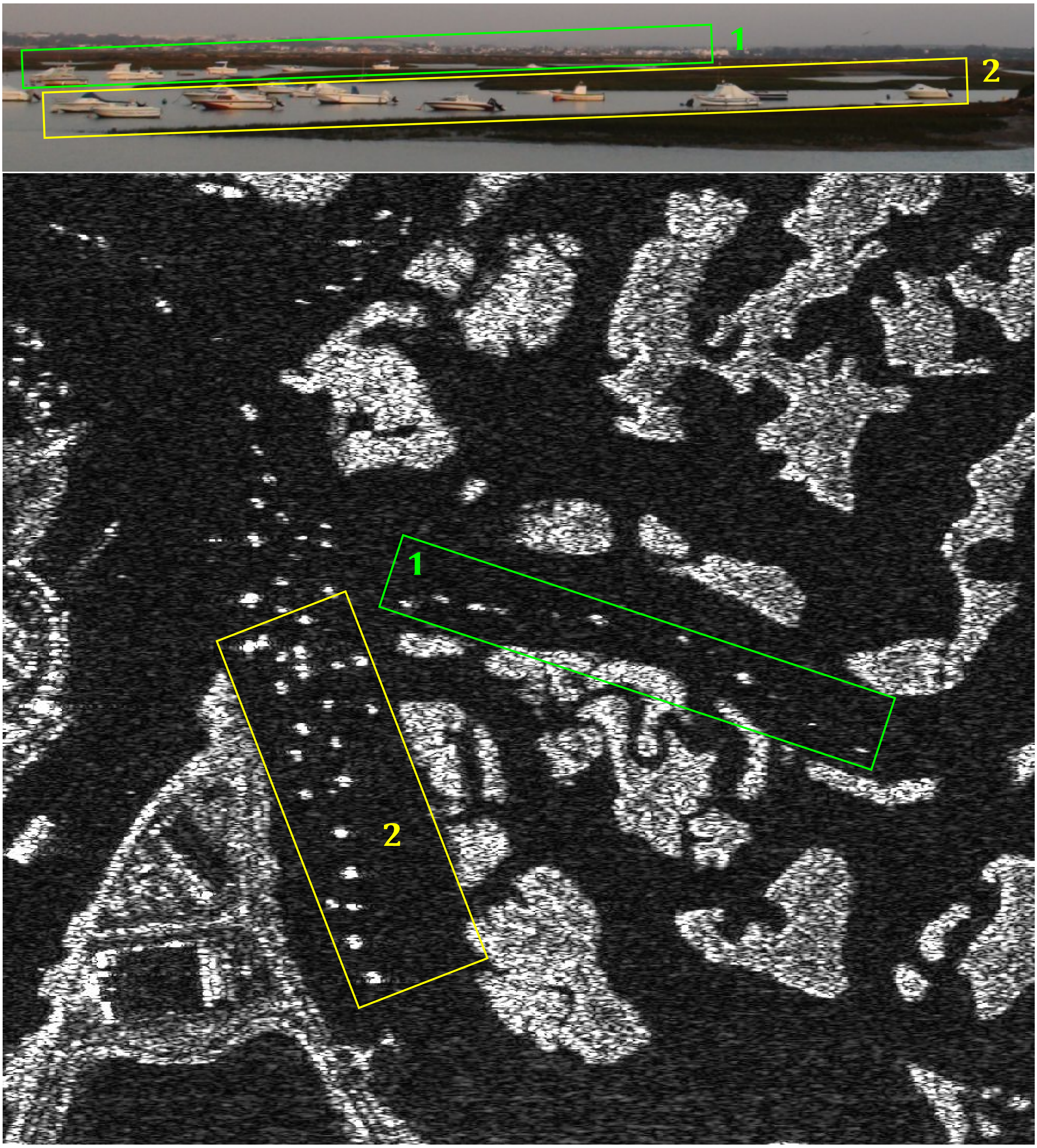


Figure 46 – Small boats detected in the SAR image, zone 4. The area (1) in green and the area (2) in yellow show two sets of small boats detected in the SAR image and the corresponding sets of boats in the ground truth data, in the present case a photo taken at the time of the satellite overpass.

5.2.2 – Radarsat2-Spotlight, 14 December 2010, El Rompido-Spain.

The SAR Satellite image acquired over El Rompido-Spain, was a Radarsat2-Spotlight, single polarization HH, Ascending pass, 14 December 2010 (Time-06:39:24). The frame (footprint) of the SAR image acquired covering El Rompido is illustrated in Figure.47.

El Rompido in Spain was the second selected place for the experiment. The area was selected due to the inland sea waters and the availability of a large number of small boats that could be used as targets of opportunity.

Figure 47 – Radarsat2 - Spotlight, single polarization HH, Descending pass, 14 December 2010 (Time-06:39:24), El Rompido – Spain.

The SAR image was calibrated using NEST, an ESA software package. Figure 47 gives an overview of the El Rompido area covered by the SAR image. A large number of small boats were detected in the SAR image. Since the small boats were spread over a wide area the SAR image has been divide in 3 zones to because it is easier to analyse the 3 zones separately.

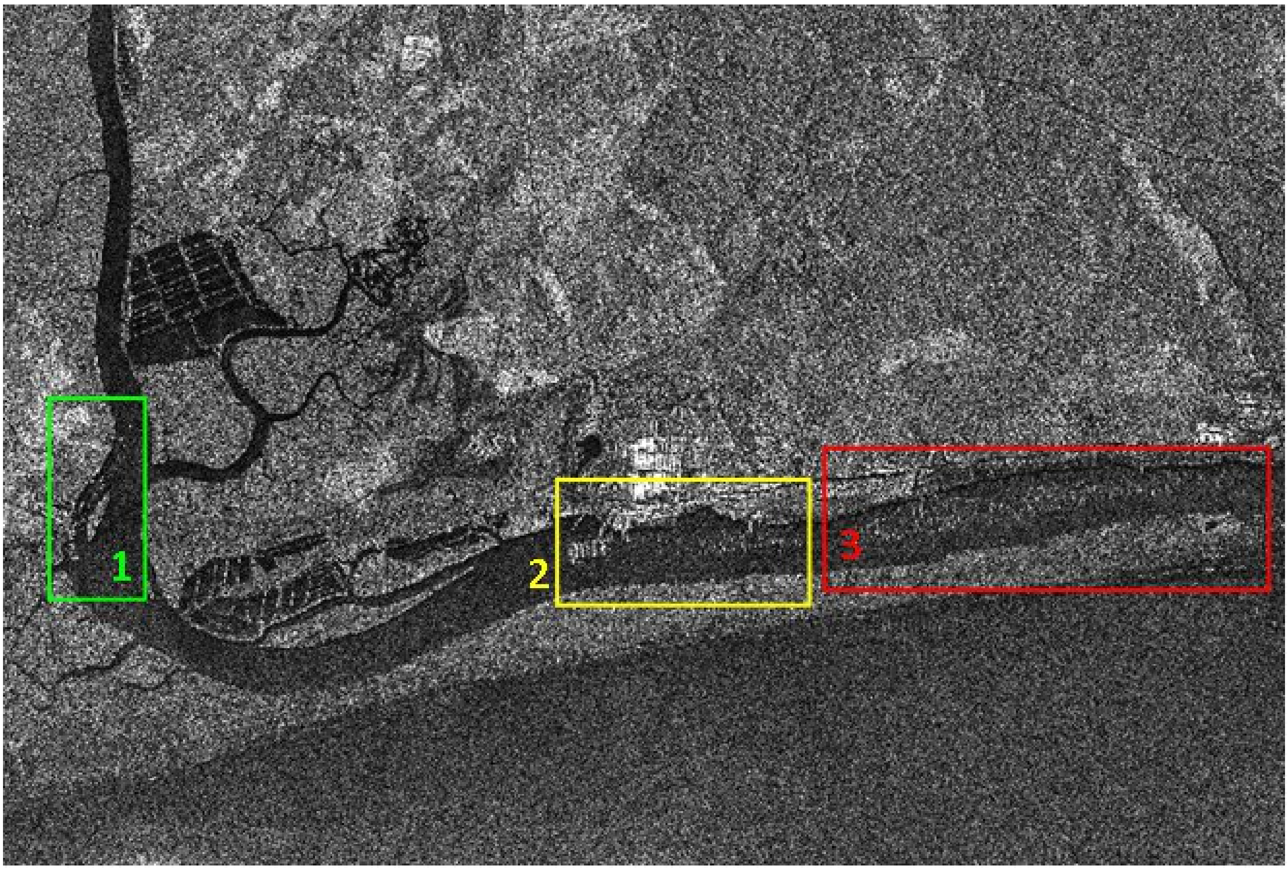


Figure 48 – Radarsat2 - Spotlight, single polarization HH, Descending pass, 14 December 2010 (Time-06:39:24), El Rompido – Spain.

Figure 49 – Google Earth optical image of El Rompido-Spain.

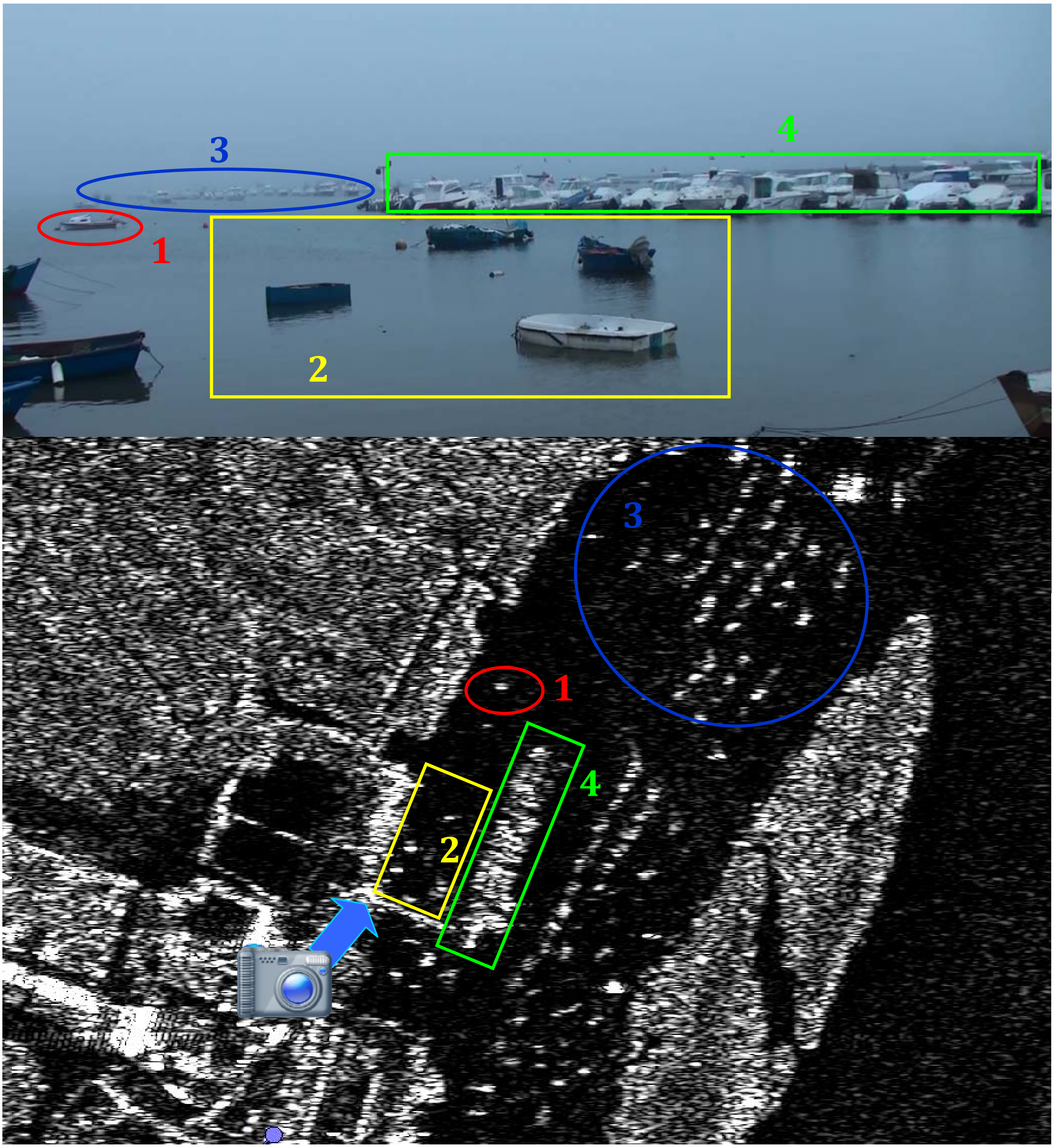


Figure 50 – Spaceborne SAR image and a photo of El Rompido-Spain (Zone 1). As it can be seen comparing the SAR image with the photo taken at the time of the satellite pass most small boats in the photo were detected in the SAR image.

Figure 50 illustrates the ground truth data and the spaceborne SAR image (zone 1). Virtually all the small boats used as targets of opportunity were detected in the SAR Satellite image. The SAR signatures of the small boats moored to the Marina are contaminated because the small boats are packed. The SAR signatures of the small boats spread around the Marina, moored on sea, allow discrimination of individual small boats.

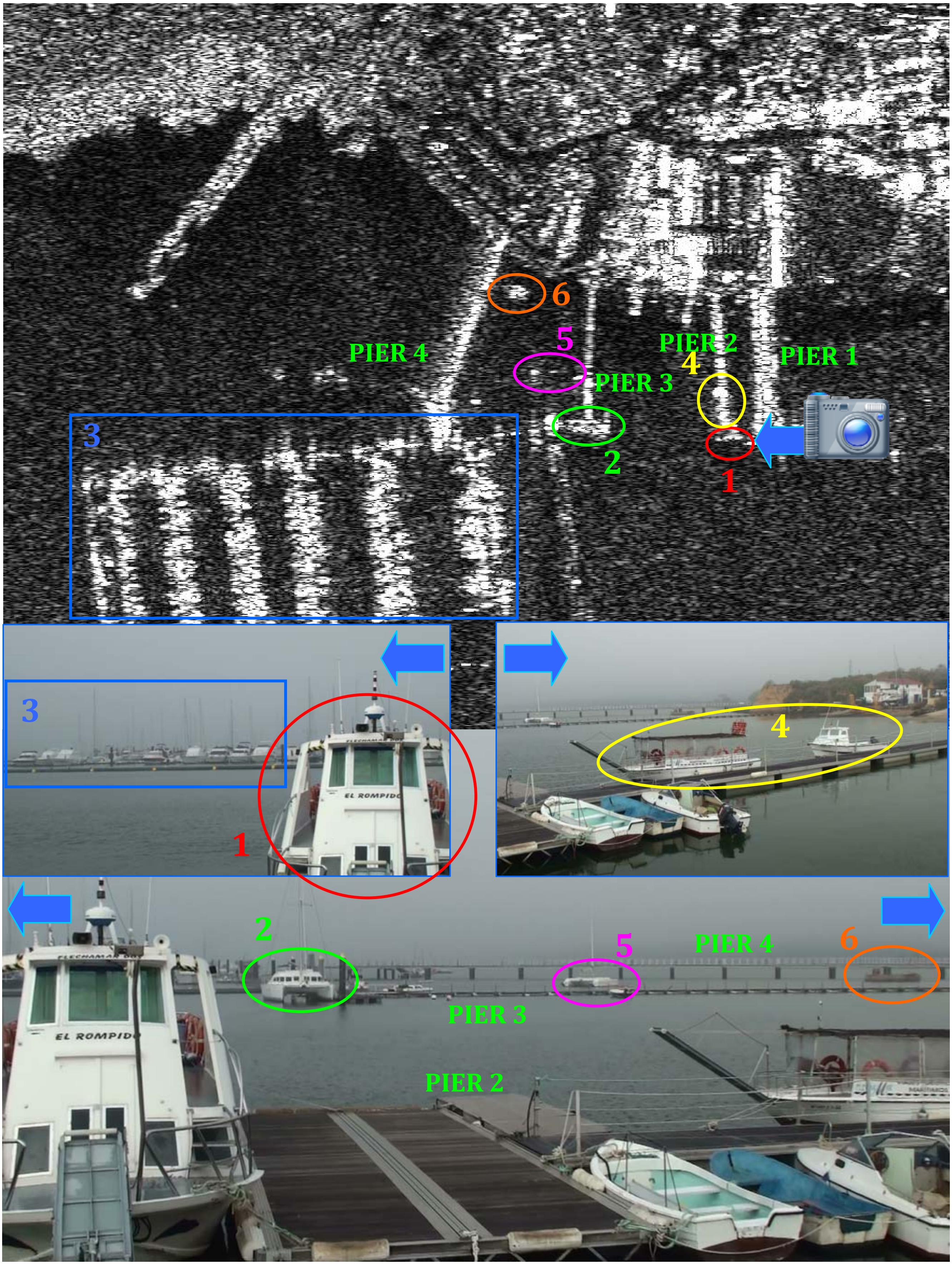


Figure 51 – Spaceborne SAR image and a photo of El Rompido-Spain (Zone 2). As it can be seen comparing the SAR image with the photos taken at the time of the satellite pass most small boats in the photos were detected in the SAR image.

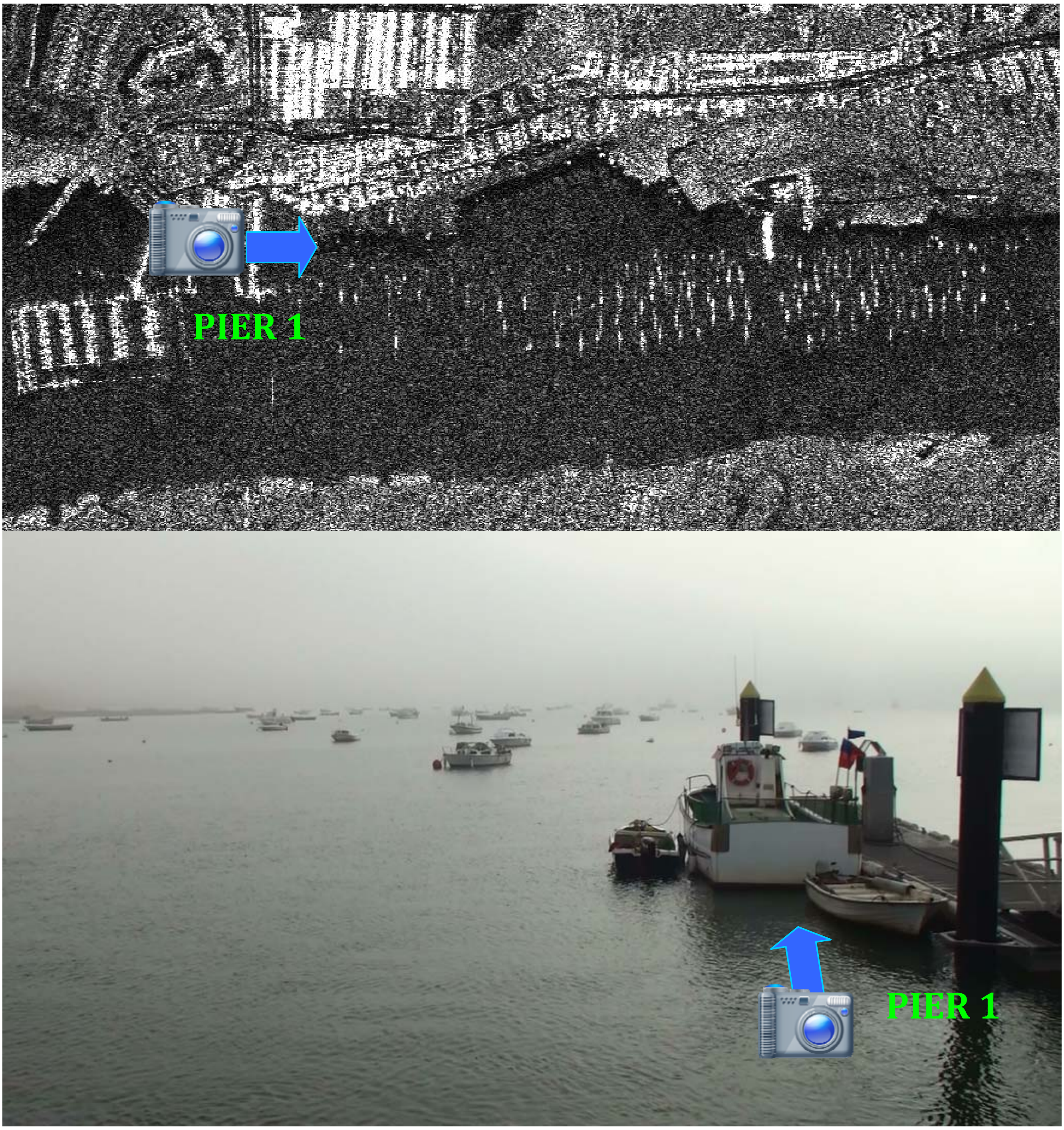


Figure 52 – Spaceborne SAR image and a photo of El Rompido-Spain (Zone 2). This photo was taken from pier 1 to the left. As it can be seen there was fog in El Rompido at the time of the satellite pass. Nonetheless, it is possible to see some of the small boats available. An analysis of the SAR image shows that a large number of small boats were detected.

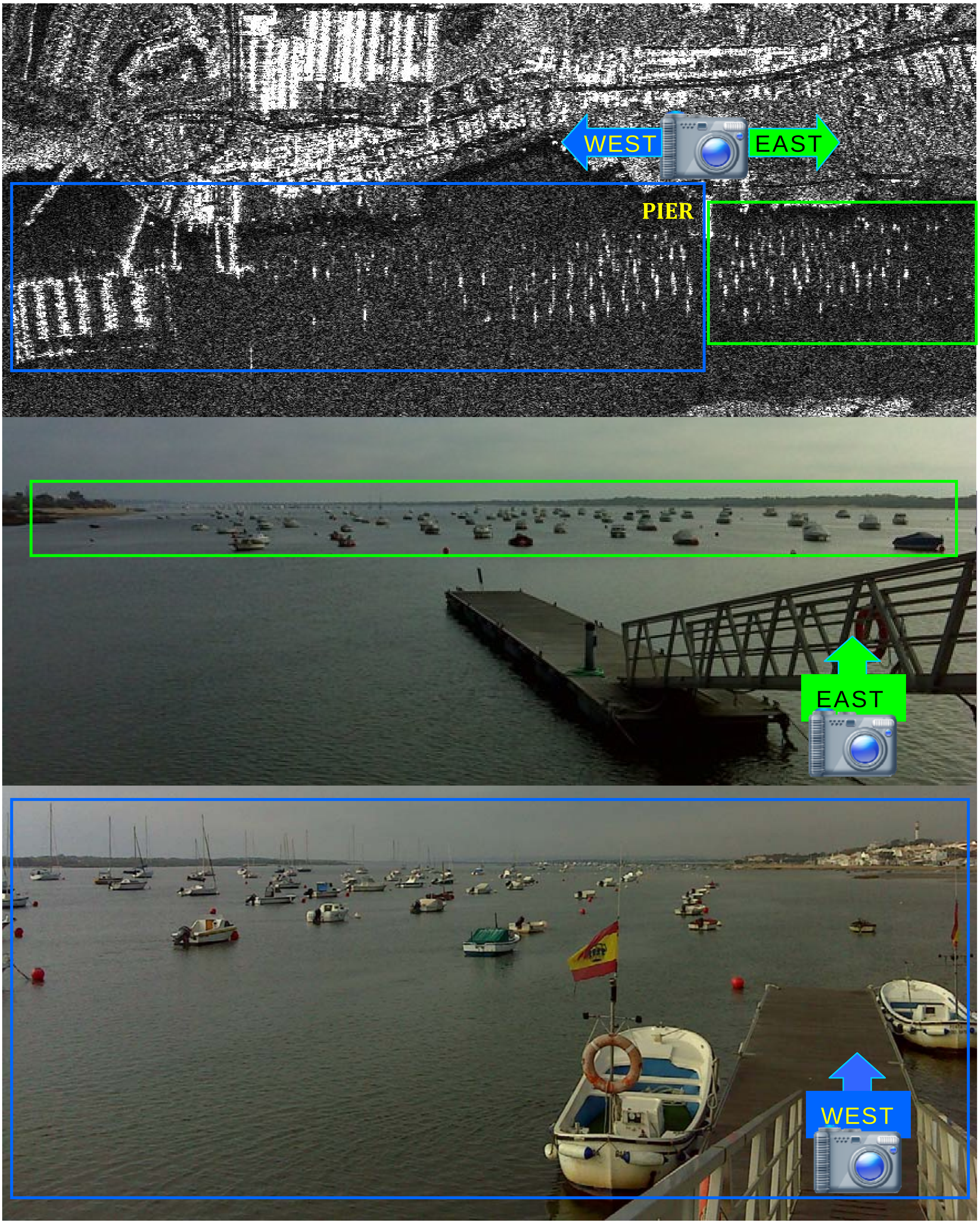


Figure 53 – Spaceborne SAR image and a two photos of El Rompido-Spain (Zone 2). These two photos were taken from the pier indicated in yellow in the SAR image. A large number of the small boats available at the time of the Satellite pass were detected.

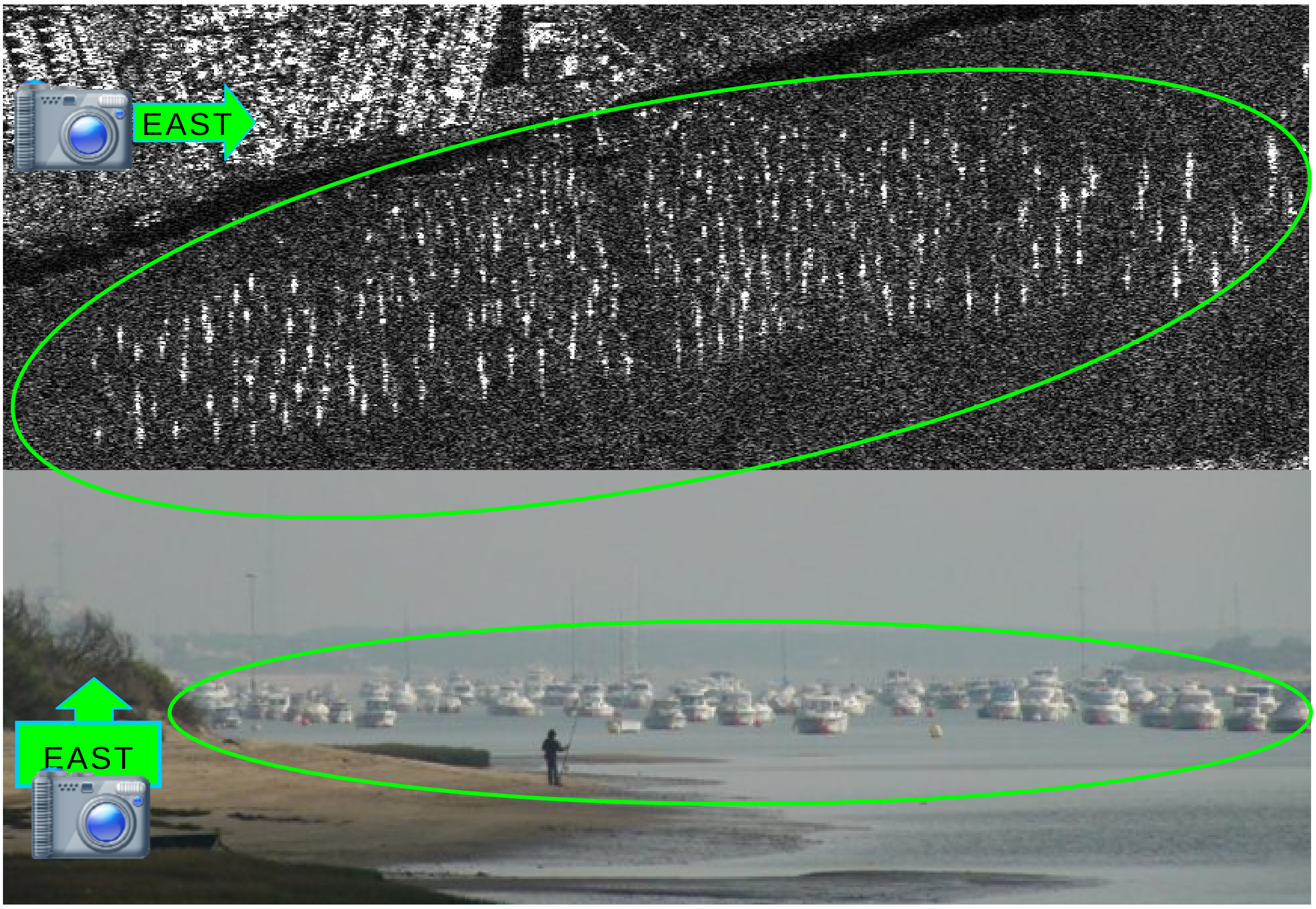


Figure 54 – Spaceborne SAR image and a two photos of El Rompido-Spain (Zone 3). A large number of the small boats available at the time of the Satellite pass were detected.

Figures 51 to 55 show the ground truth data for zones 2 and 3 and the respective SAR images.

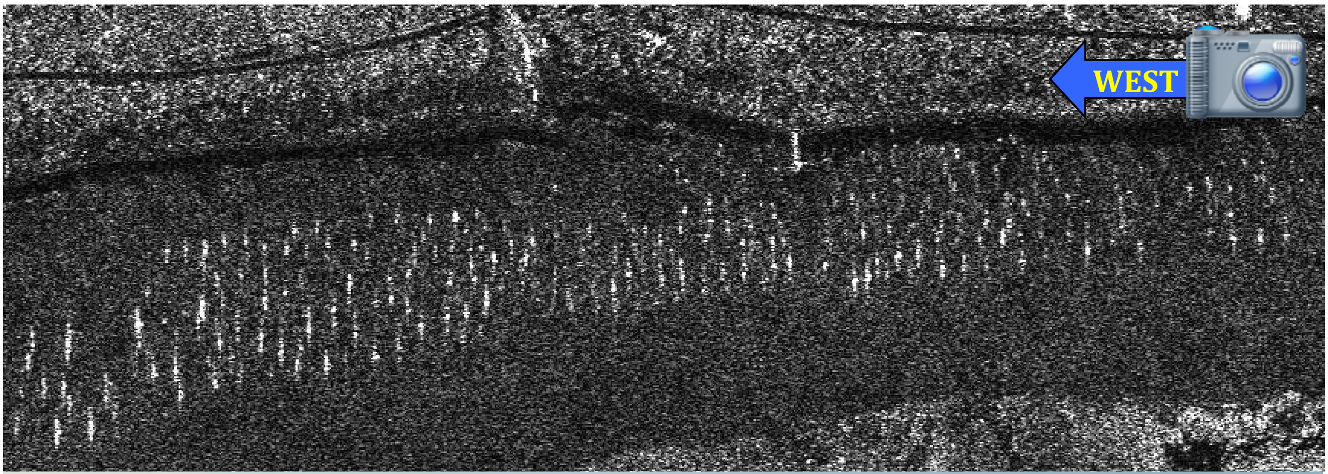


Figure 55 – Spaceborne SAR image and a two photos of El Rompido-Spain (Zone 3). A large number of the small boats available at the time of the Satellite pass were detected.

Figures 56 to 63 show the ground truth data for zones 2 and 3 and the respective SAR images.

5.2.3 – TerraSAR-X-Spotlight, 15 December 2010, Sagres.

Figure 56 illustrates the SAR image acquired over Sagres and a photo taken at the time of the satellite pass. The wind speed was 3-5m/s and the wave height 0.5-1m. Some small boats were detected.

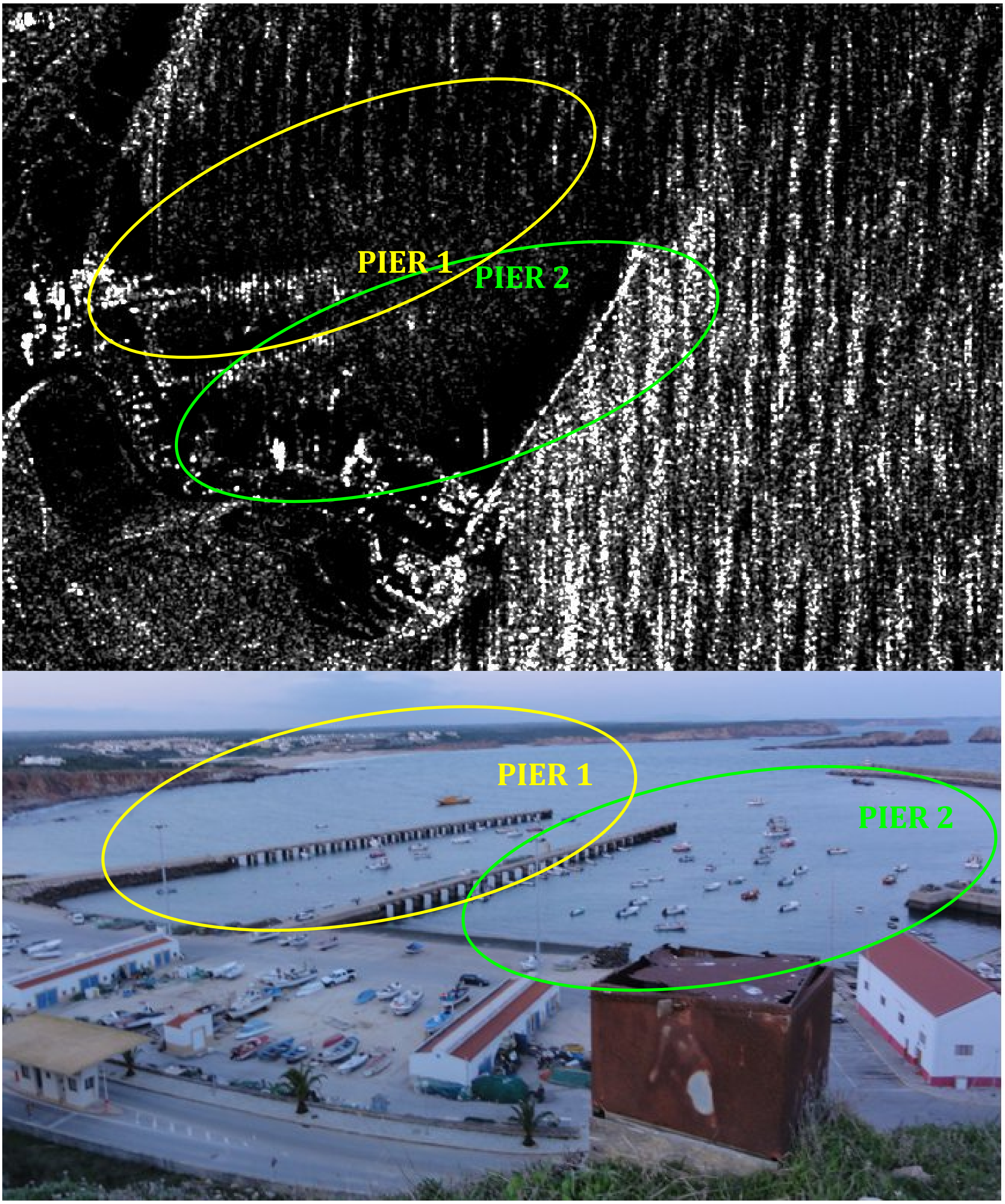


Figure 56 – Spaceborne SAR image and a photo of Sagres-Portugal. A large number of the small boats available at the time of the Satellite pass were detected.

5.2.4 – Radarsat-2 - Spotlight, 16 December 2010, Punta Umbria

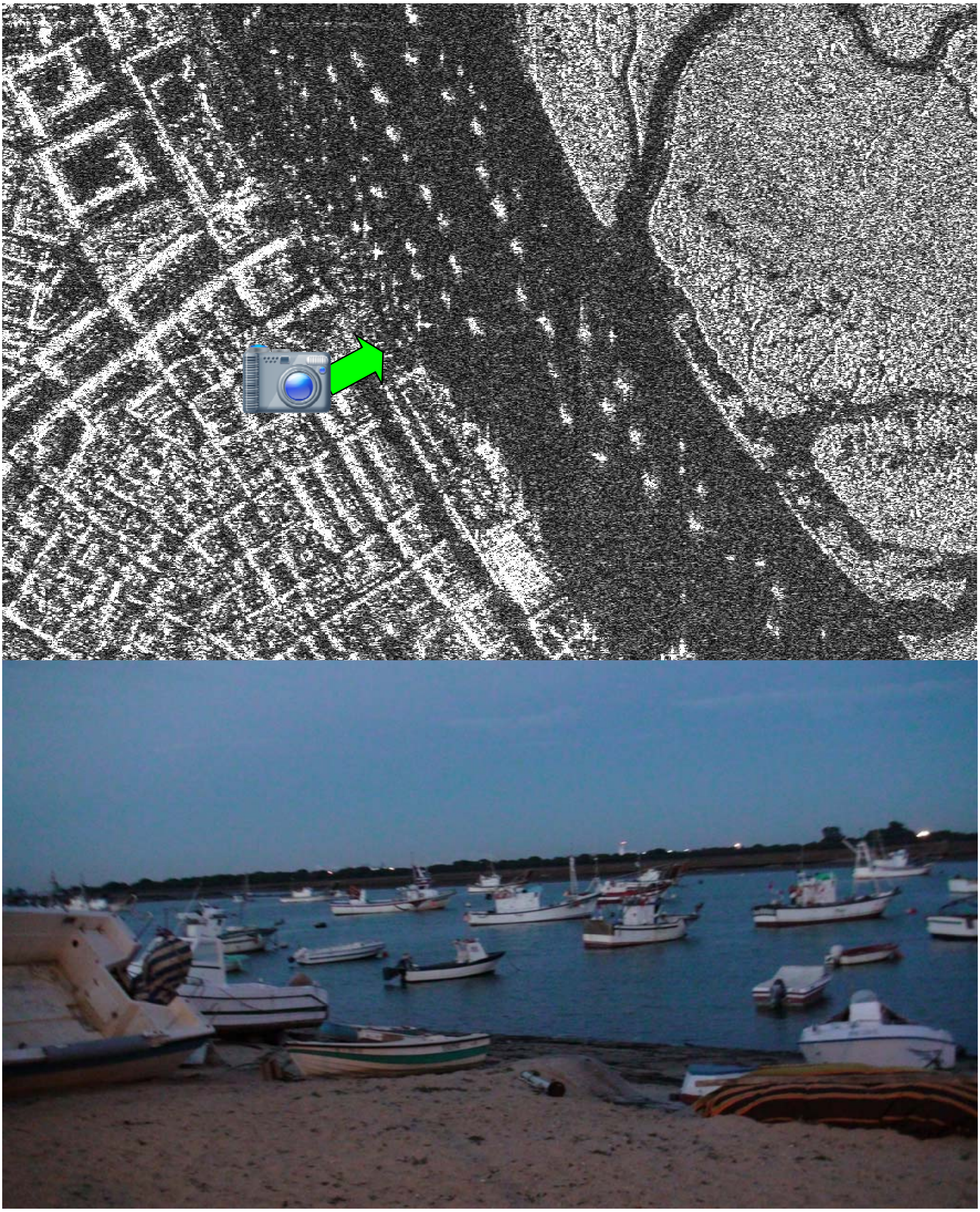


Figure 57 – Spaceborne SAR image and a photo of Punta Umbria. A large number of the small boats available at the time of the Satellite pass were detected.

5.2.5 – Radarsat-2 - Spotlight, 18 December 2010, Cadiz

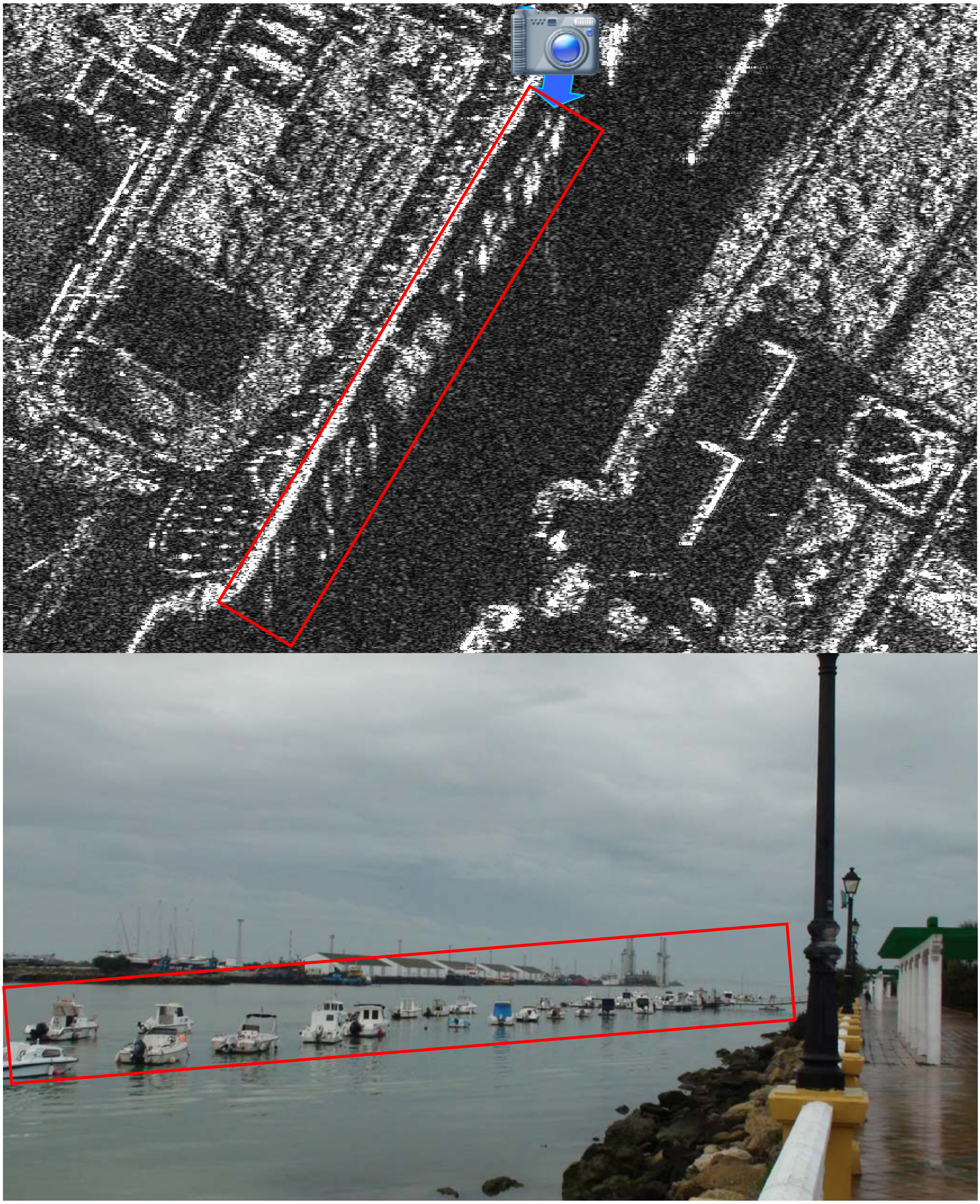


Figure 58 – Spaceborne SAR image and a photo of Punta Umbria. A large number of the small boats available at the time of the Satellite pass were detected.

5.2.6 – Radarsat-2 - Spotlight, 23 December 2010, Isla Cristina

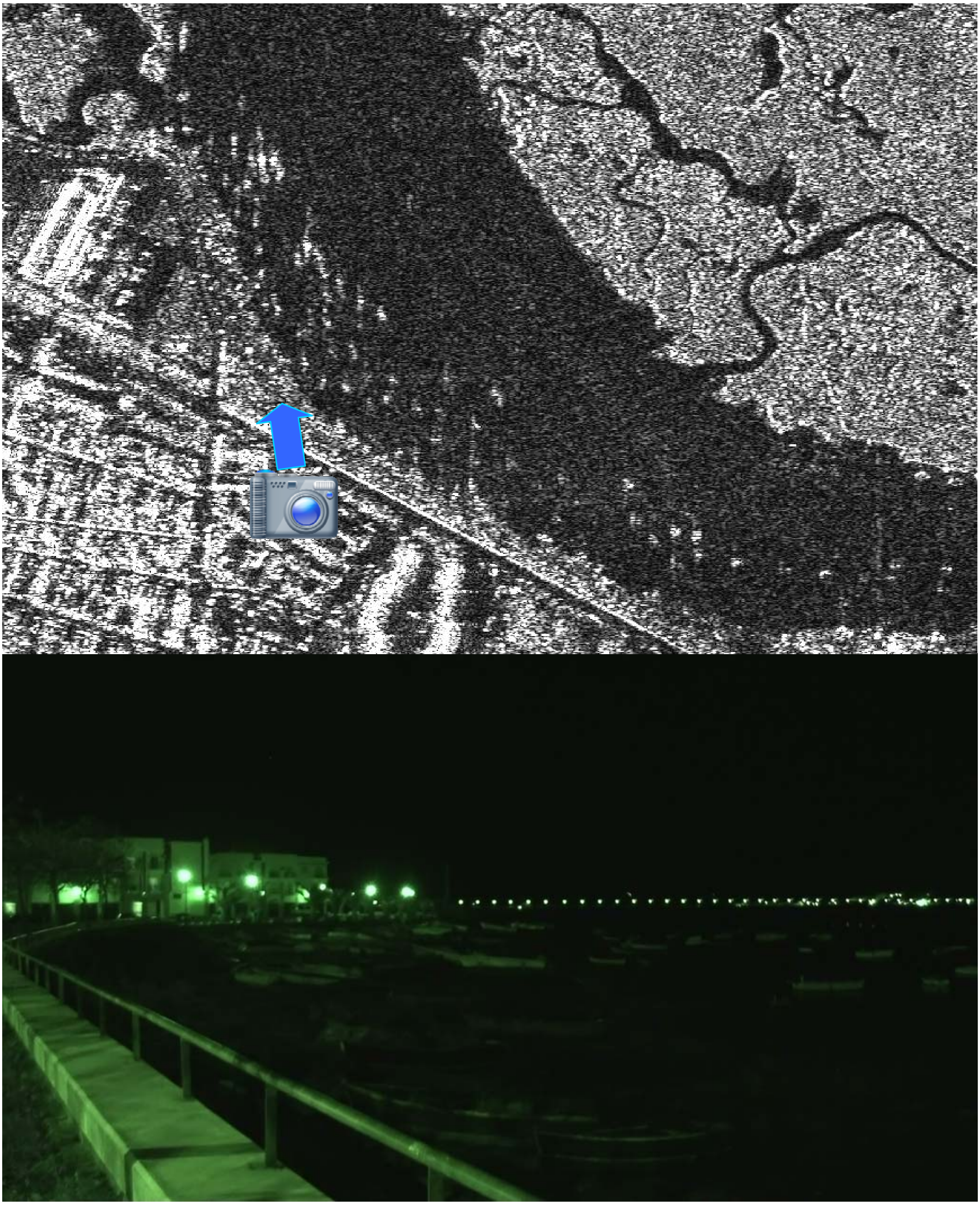


Figure 59 – Spaceborne SAR image and a photo of Isla Cristina. A large number of the small boats available at the time of the Satellite pass were detected.

Figure 60 – Spaceborne SAR image and a photo of Isla Cristina. Another set of small boats available near a bridge. Most of the small boats were detected.

5.2.7 – TerraSAR-X - Spotlight, 24 December 2010, Cascais

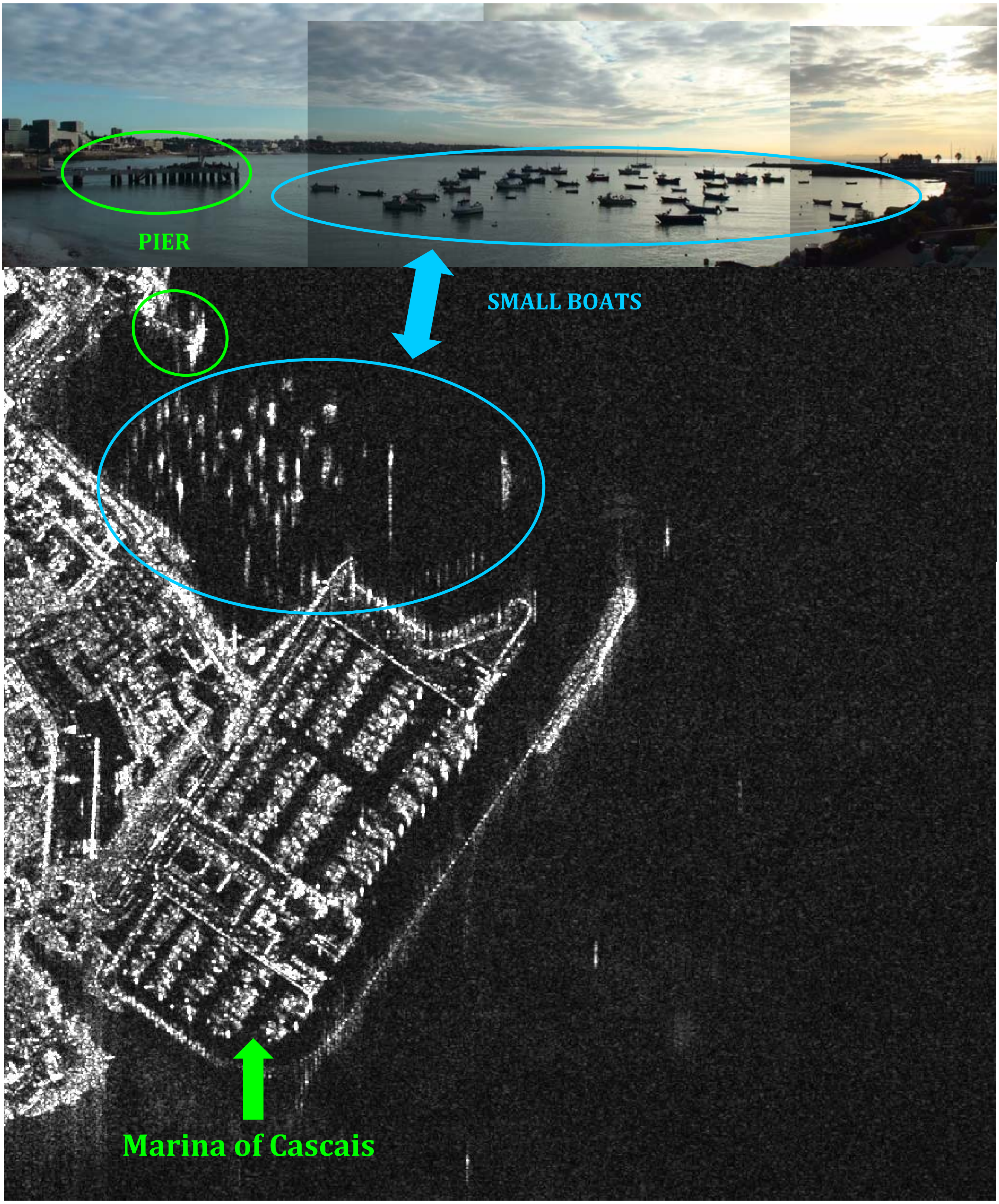


Figure 61 – TerraSAR-X Spotlight image acquired over Cascais-Portugal and a photo of Cascais. Most of the small boats available at the Bay of Cascais were detected in the SAR image.

5.2.8 – Radarsat-2 - Ultrafine, 24 December 2010, Cascais

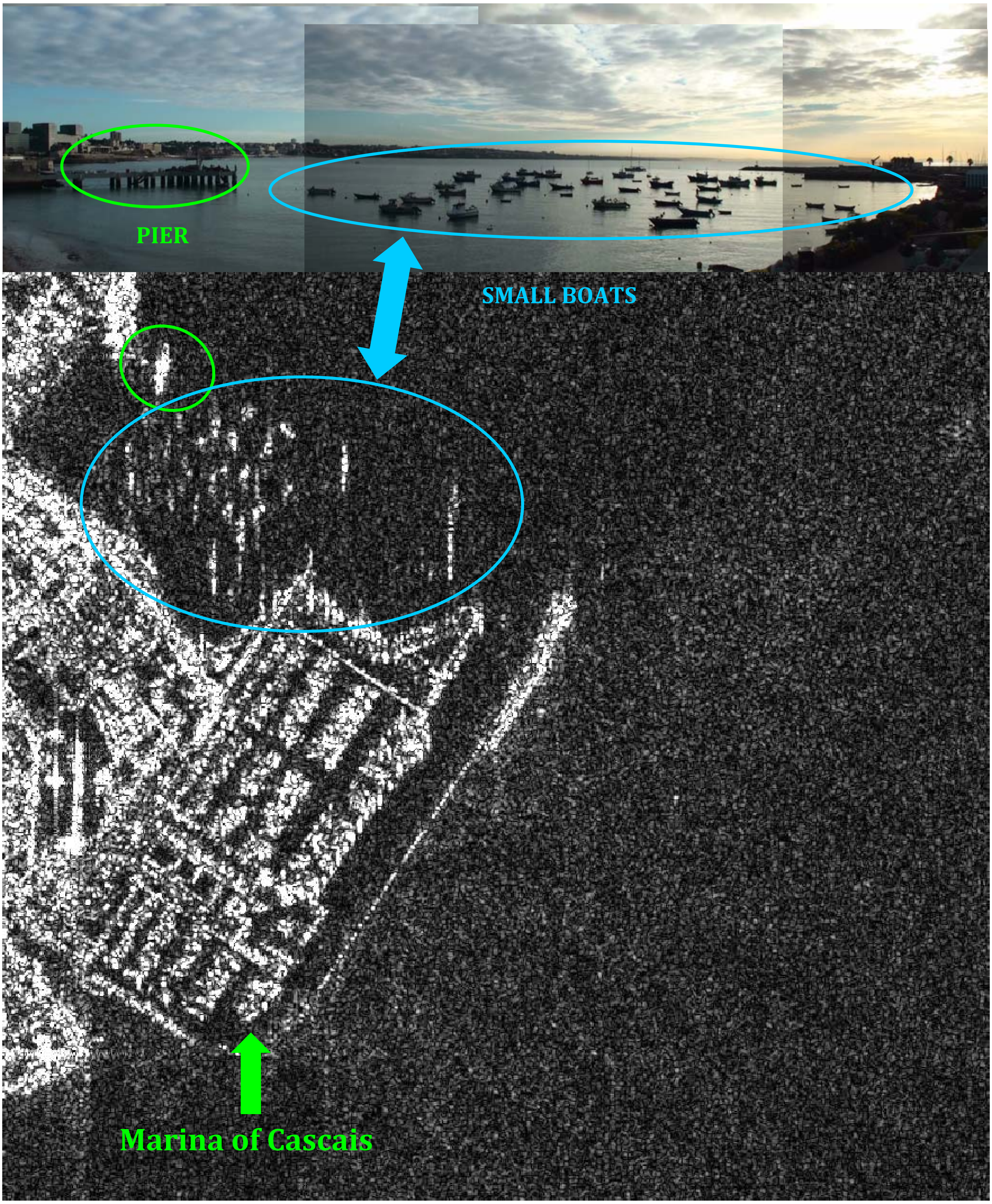


Figure 62 – TerraSAR-X Spotlight image acquired over Cascais-Portugal and a photo of Cascais. Most of the small boats available at the Bay of Cascais were detected in the SAR image.

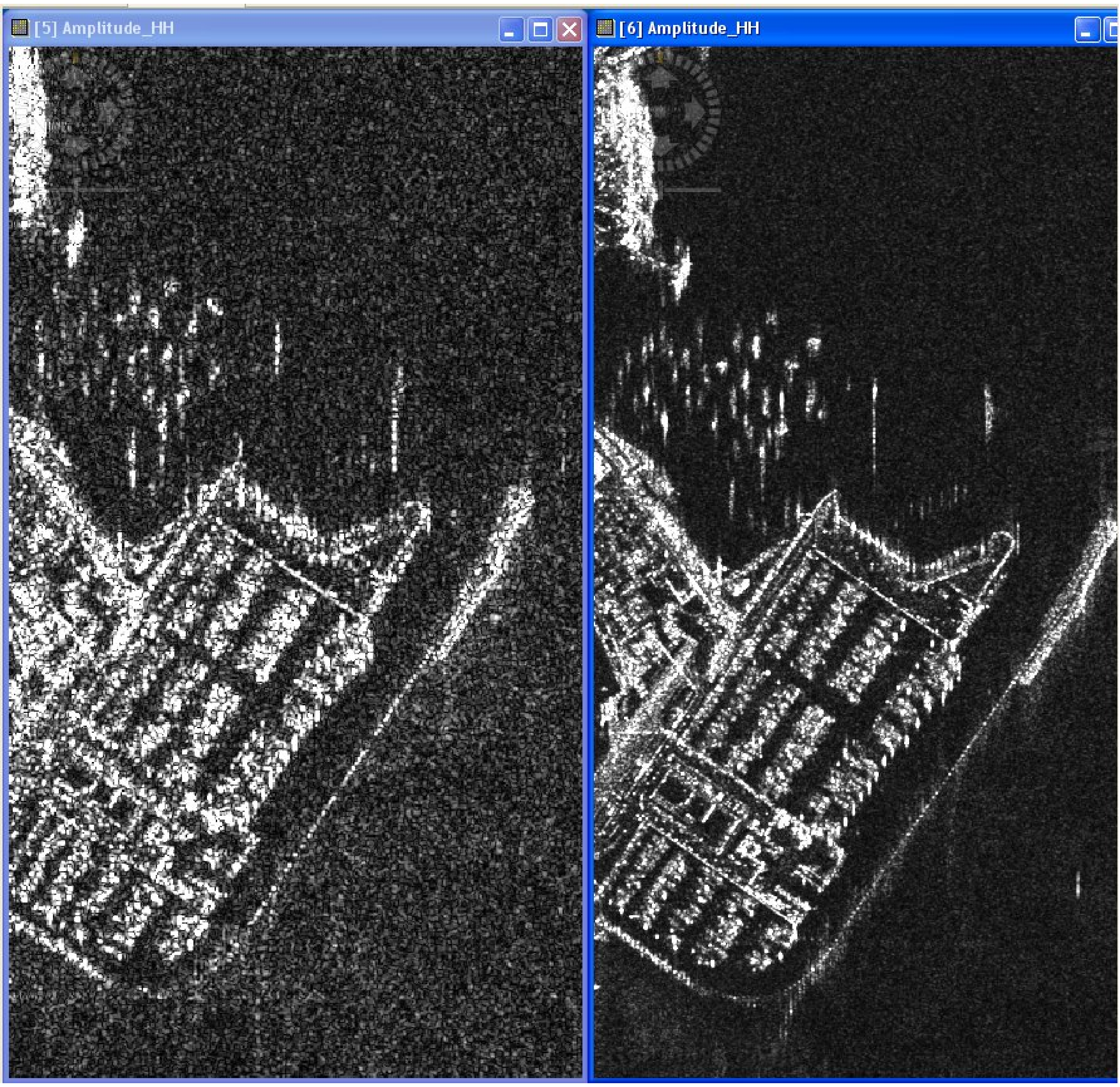


Figure 63 – On the left the RS2-Ultrafine image of the Marina and Bay of Cascais acquired on 24 Dec. 2010 (06:47:26 UTC). On the right the TerraSAR-X Spotlight image acquired over Cascais-on 24 Dec. 2010. (06:46:40 UTC). The two images have been acquired just 46 seconds apart. Due to its higher resolution the Spotlight image on the right provides more detail. It looks sharper. The resolution of the Radarsat-Ultrafine image on the left is approximately 3m. The resolution of the TerraSAR-X Spotlight image on the right is about 1m.

5.3 – Summary of the Analysis of the SAR Satellite Imagery

This section gives a summary of the preliminary visual analysis of the 8 SAR Satellite images acquired in this campaign. The images acquired are listed in Table 3. Five of the eight images have been acquired over inland waters and the remaining three over Port / Bay waters. Each image will now be addressed in turn in the next sections.

Table 3 – List of SAR Satellite images acquired in this maritime surveillance campaign.

PORTUGAL and SPAIN							
Date	**Pass**	**Time (UTC)**	**Area Selected**	**Satellite / Mode**	**Pol.**	**Scenario**	**Small Boats Detected?**
13/12/10	ASC	18:24:04	Sancti Petri–SP	RS-2 / Spotlight	HH	Inland Waters	Yes
14/12/10	DES	06:39:24	El Rompido – SP	RS-2 / Spotlight	HH	Inland Waters	Yes
15/12/10	ASC	18:23:25	Sagres – Portugal	TSX / Spotlight	HH	Port / Bay	Yes
16/12/10	ASC	18:36:47	Punta Umbria–SP	RS-2 / Spotlight	HH	Inland Waters	Yes
18/12/10	DES	06:22:55	Cadiz – Spain	RS-2 / Spotlight	HH	Inland Waters	Yes
23/12/10	ASC	18:32:38	Isla Cristina – SP	RS-2 / Spotlight	HH	Inland Waters	Yes
24/12/10	DES	06:46:40	Cascais – Portugal	TSX / Spotlight	HH	Port / Bay	Yes
24/12/10	DES	06:47:26	Cascais – Portugal	RS-2 / Ultrafine	HH	Port / Bay	Yes

5.3.1 – Radarsat2-Spotlight, 13 December 2010, Sancti Petri-La Barrosa-Spain.

The area of Sancti Petri-La Barrosa is very interesting because it provides several zones with different exposures to the sea state effect and a wide variety of boats, such as recreational/leisure boats, fishing boats, cargo/tankers, etc. with sizes ranging from 3m up to 50m or more. Most boats available, however, have sizes in the range of 5m-10m. For convenience, the area has been divided in 4 zones. Zones 2 and 3 are more exposed to sea state changes and zones 1 and 4 are less exposed. The type and size of the boats is also different in the 4 zones. Zone 1 has mainly small boats with sizes ranging from 3m to 5m. Zone 4 has mainly leisure boats with sizes ranging from 3m to 10m. Zone 2 has a mix of leisure boats and fishing boats with sizes in the range of 3m to 10m and two shipwrecks with approximate size of 20m. Finally, zone 1 has a Marina for leisure boats and a large number of sailboats and fishing boats with sizes ranging from 3m to 15m or more. Zones 1 and 2 have boats on land and in the water. Zones 2 and 4 have mainly boats in the water. Another advantage of Sancti Petri is that it is relatively easy to collect ground truth data because the 4 zones are close to each other and the access to the sea is also easy.

Most of the small boats in the water were detected in the SAR image. Some boats on land were detected but it is more difficult to identify them because their SAR signatures are difficult to identify due to the low contrast with the background.

5.3.2 – Radarsat2-Spotlight, 14 December 2010, El Rompido-Spain.

The area of El Rompido is also interesting because it has hundreds of small boats of different types, sizes and materials. It also has relatively easy access to the sea. The area has been divided into 3 zones to facilitate the analysis. The main disadvantage is that Zone 1 (Cabezo de la Bella) is relatively far from zones 2 and 3 (El Rompido). The access to the sea in zone 1 is not easy. Another drawback is the fact that the boats in zones 2 and 3 are spread along more than 6km and the access to the sea is not straightforward.

As with the previous image, most of the small boats in the water were detected in the SAR image. Some boats on land were detected but their identification is not easy for the same reason as with the first image.

5.3.3 – TerraSAR-X-Spotlight, 15 December 2010, Sagres.

The third image was acquired over the Port and Bay of Sagres in Portugal. A variety of boats was available and it was easy to collect ground truth data. The wind speed was 3-5m/s and the wave height 0.5-1m. Although some small boats were detected, the quality of the image was affected by the sea state. The image shows high frequency waves breaking. The resulting sea clutter makes it difficult to isolate some targets from the background clutter.

5.3.4 – Radarsart2-Spotlight, 16 December 2010, Punta Umbria – Spain.

The fourth SAR image was acquired over Punta Umbria. The area has a large number of boats of different sizes and types (e.g. leisure boats, fishing boats, etc.). It was relatively easy to collect the ground truth data.

5.3.5 – Radarsat-2 - Spotlight, 18 December 2010, Cadiz

The fifth spaceborne SAR image was acquired over Cadiz. A large number of small boats were detected. The SAR signatures of the small boats exhibit significant smearing, apparently due the wind speed at the time of the satellite pass.

5.3.6 – Radarsat-2 - Spotlight, 23 December 2010, Isla Cristina

The sixth SAR Satellite image was acquired over Isla Cristina in Spain. The small boats were spread over several areas of Isla Cristina located a few kilometers apart. It was night at the time of the satellite pass, which made the ground truth data collection more difficult than usual. A large number of small boats were detected.

5.3.7 – TerraSAR-X - Spotlight, 24 December 2010, Cascais

The seventh spaceborne SAR image was acquired over the marina and Bay of Cascais. A significant number of small boats, which have been used as targets of opportunity, were available in the Bay of Cascais.

5.3.8 – Radarsat-2 - Ultrafine, 24 December 2010, Cascais

The eighth SAR Satellite image was acquired over the marina and Bay of Cascais just about 46 seconds apart the seventh SAR image. Although the resolution of this image (about 3m) is lower than the resolution of the previous SAR image, virtually all the small boats detected in the previous image have also been detected in this one.

6. – Preliminary Conclusions and Discussion

This chapter gives a quantitative analysis for each spaceborne SAR image acquired and describes the preliminary conclusions of this spaceborne SAR small boat detection experiment.

6.1 – Quantitative Analysis of the Spaceborne SAR Images

In order to allow a quantitative analysis of the data, all the spaceborne SAR images were calibrated using ESA's NEST software package, version 4B. The inputs were the SAR images acquired and the outputs were the Radiometric Calibration (Sigma Naught (σ°)) expressed in terms of intensity and in decibel (dB), the Radar Brightness (β°) and the Radiometric Normalisation (gamma naught (γ°)).

6.1.1 – Radarsat2-Spotlight, 13 December 2010, Sancti Petri-La Barrosa

Figure 64 illustrates the Amplitude and Intensity bands of the Radarsat2-Spotlgiht image (13Dec.2010).

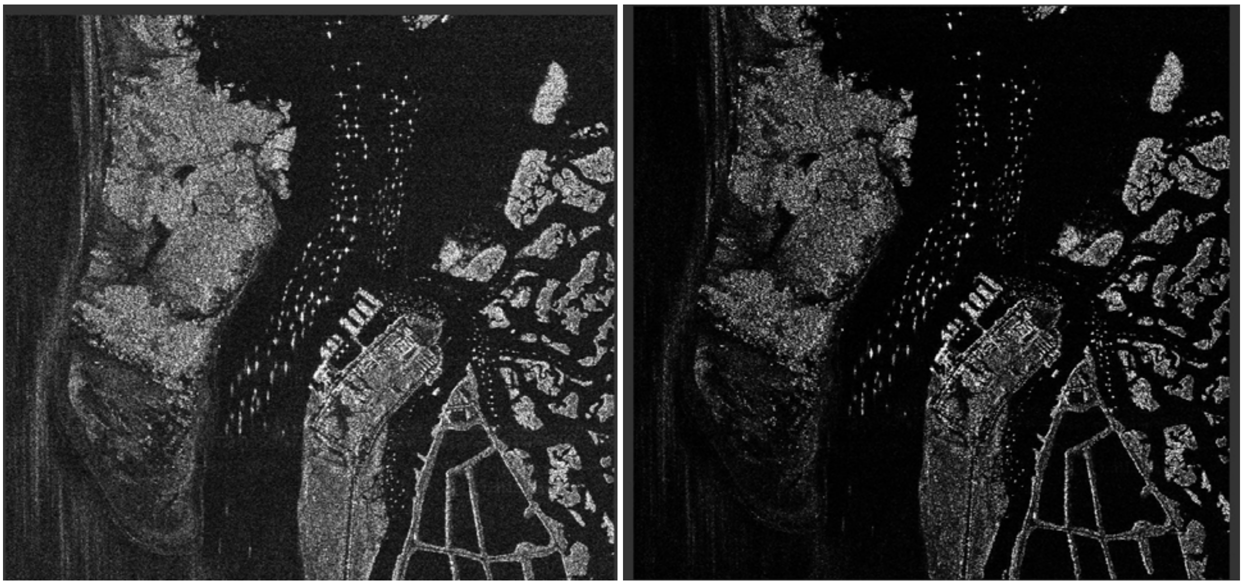


Figure 64 – Radarsat2-Spotlight, 13Dec.2010 - On the left, the Amplitude band. On the right the Intensity band.

Figure 65 illustrates the Sigma Naught Coefficient of the Radarsat2-Spotlgiht image (13Dec.2010) expressed in terms of intensity and decibel (dB).

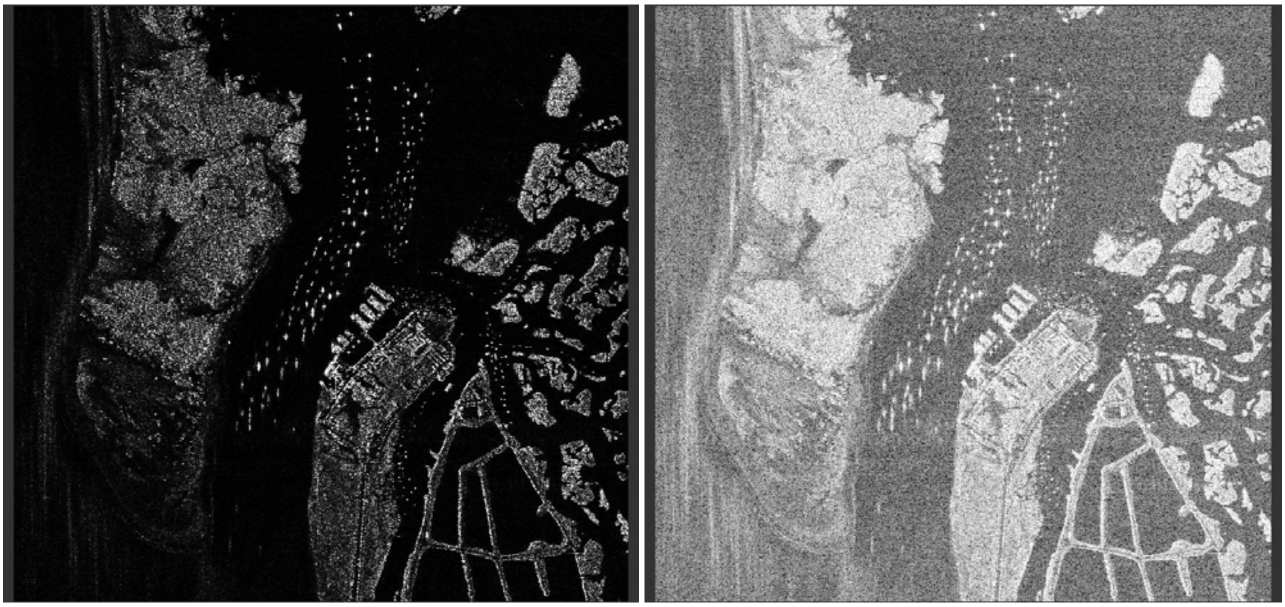


Figure 65 – Radarsat2-Spotlight, 13Dec.2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 66 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the Radarsat2-Spotlgiht image (13Dec.2010) expressed in dB.

Figure 66 – Radarsat2-Spotlight, 13Dec.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 67 shows the Sigma Naught (σ°) in dB after some colour manipulation and the histogram of the Sigma Naught (σ°) image.

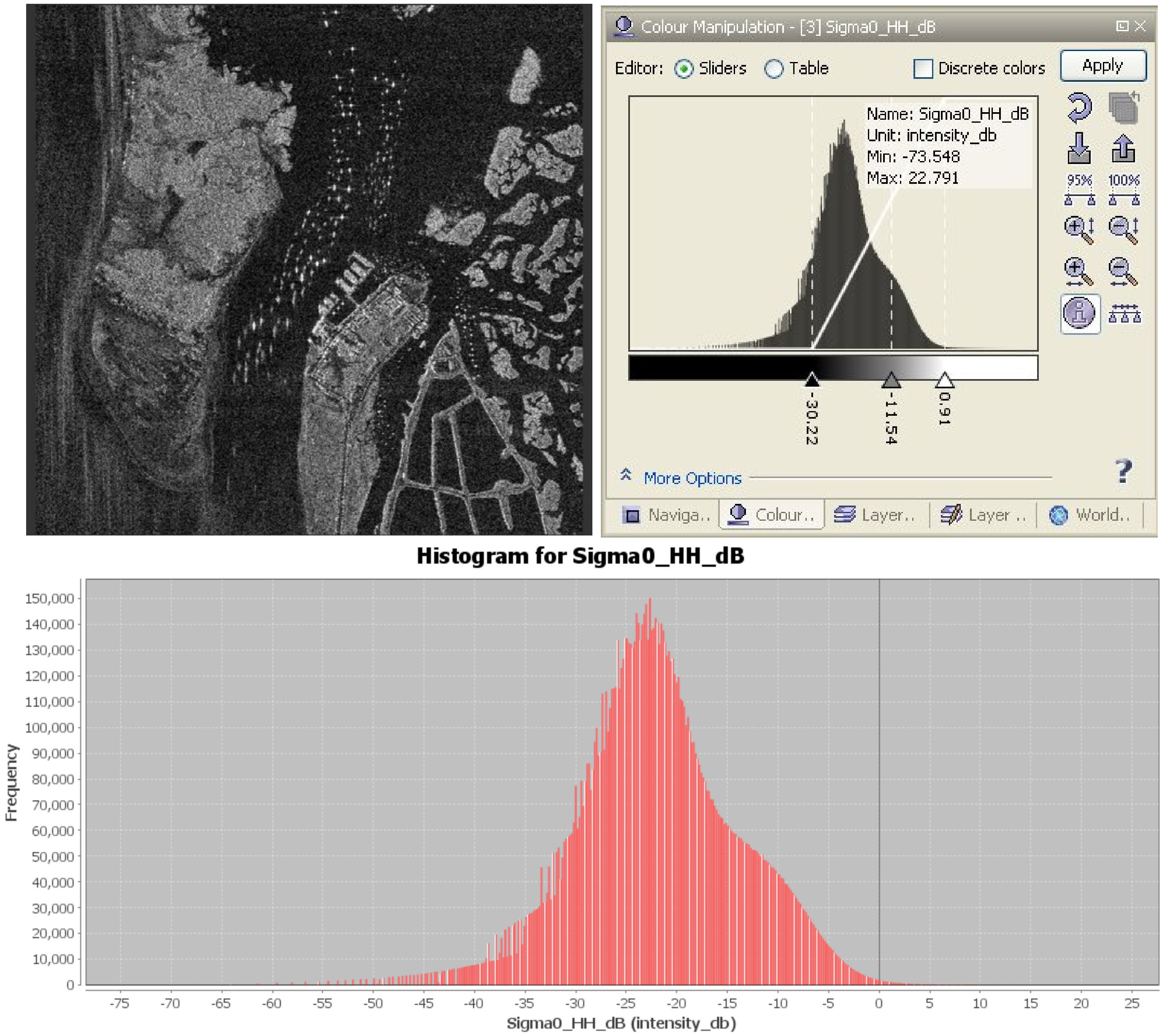


Figure 67 – Radarsat2-Spotlight, 13Dec.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 4 gives the statistics of the Sigma Naught (σ°) Radarsat2-Spotlight image (13Dec.2010). The Sigma Naught (σ°) range from -73.5 dB up to 22.8 dB. The Mean value is -21.9 dB, the Median is -22.4 dB and the standard deviation is 7.9 dB.

Table 4 – Statistics of the Radarsat2-Spotlight 13Dec.2010 (18:24h UTC).

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	1819510	
Number of considered pixels:	1819510	
Ratio of considered pixels:	100.0 %	
Minimum:	-73.5	intensity_db
Maximum:	22.8	intensity_db
Mean:	-21.9	intensity_db
Median:	-22.4	intensity_db
Std-Dev:	8.0	intensity_db
Coefficient of Variation:	0.7	intensity_db

Fig.68 illustrates the 4 sections in which the image has been divided for analysis purposes. The sizes of the small boats in sections 1 and 2 range from about 3m to 6m. In section 4 the small boats range from about 5m to 12m. Finally, in section 3 the small boats range from about 6m to 15m. Checking the radar backscattering coefficient of the targets (small boats) detected in the different sections, the maximum Sigma Naught values (σ°) in sections 1 (in yellow) and 2 (in magenta) is about 9.6 dB. In section 4 the maximum Sigma Naught values (σ°) are about 12.0 dB and in section 3 about 22.0 dB.

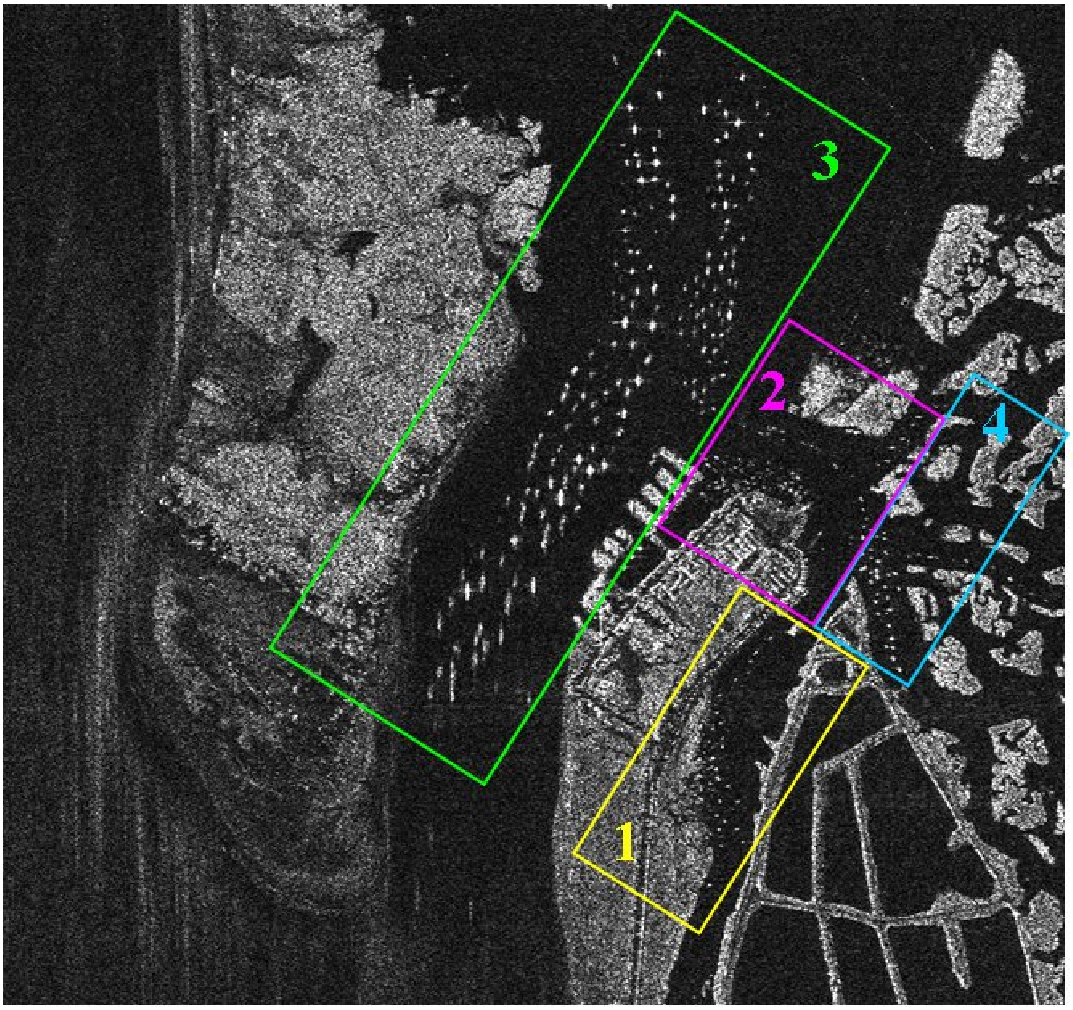


Figure 68 – Radarsat2-Spotlight, 13Dec.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

6.1.2 – Radarsat2-Spotlight,14Dec.2010(06:39h UTC), El Rompido, Spain

Figure 69 illustrates the Amplitude and Intensity bands of the Radarsat2-Spotlgiht image (14Dec.2010)

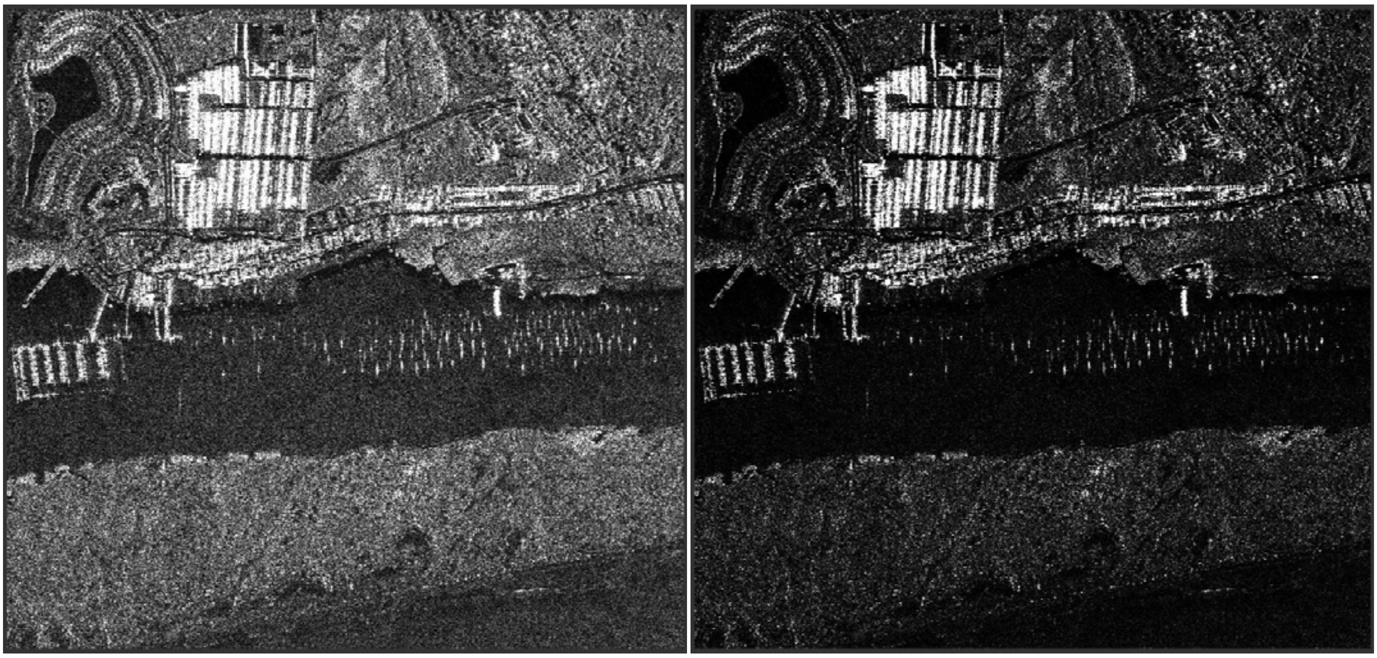


Figure 69 – Radarsat2-Spotlight, 14Dec.2010 - On the left, the Amplitude band. On the right the Intensity band.

Figure 70 illustrates the Sigma Naught Coefficient of the Radarsat2-Spotlgiht image (14Dec.2010) expressed in terms of intensity and decibel (dB).

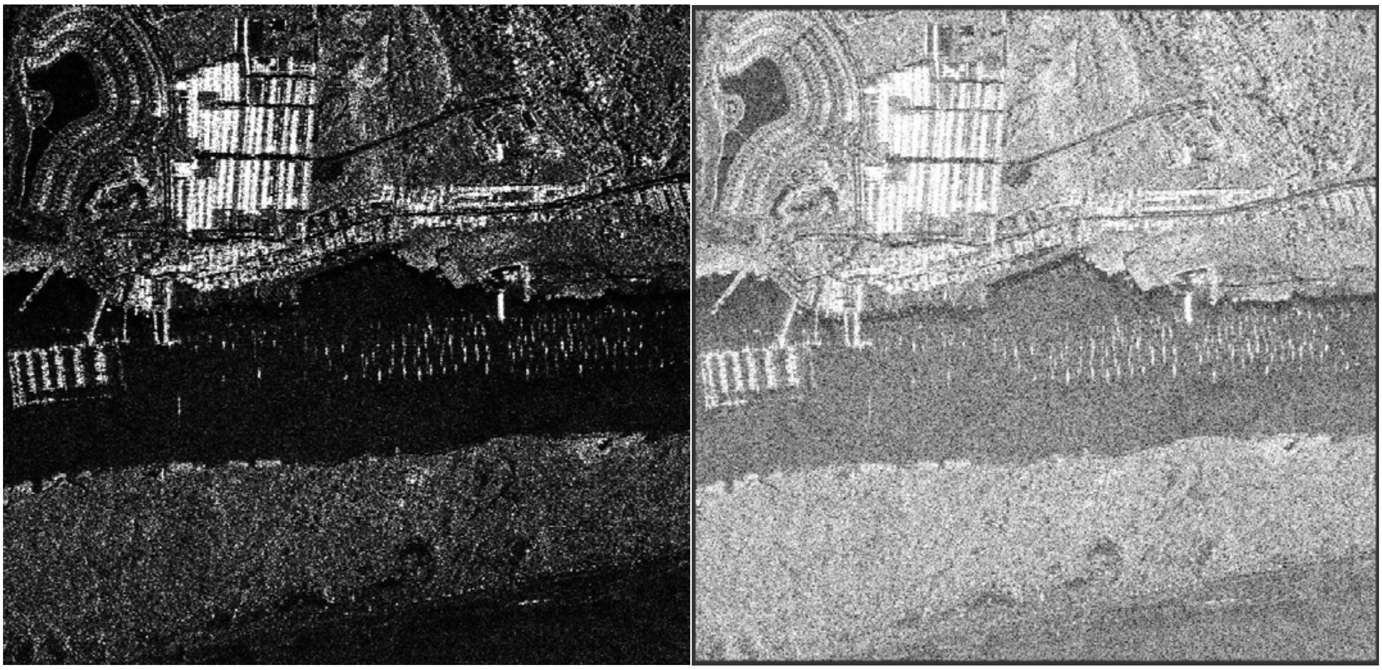


Figure 70 – Radarsat2-Spotlight, 14Dec.2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 71 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the Radarsat2-Spotlgiht image (14Dec.2010) expressed in dB.

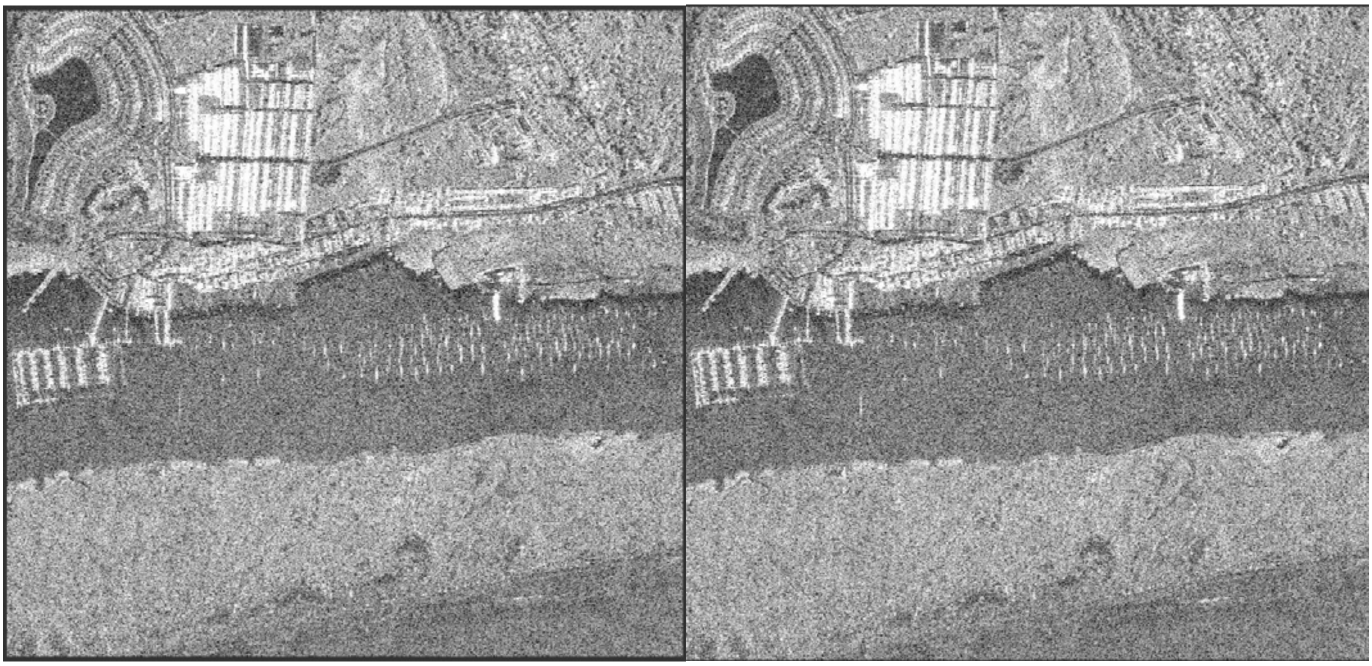


Figure 71 – Radarsat2-Spotlight, 14Dec.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Table 5 gives the statistics of the Sigma Naught (σ°) Radarsat2-Spotlight image (14Dec.2010). The Sigma Naught (σ°) range from -74.7 dB up to 9.6 dB. The Mean value is -13.5 dB, the Median is -13.5 dB and the standard deviation is 7.6 dB.

Table 5– Statistics of the Radarsat2-Spotlight 14Dec.2010 (06:39h UTC)

Statistics	Values	Unit
Only ROI-Mask pixels considered: Number of pixels total: Number of considered pixels: Ratio of considered pixels:	No 14926878 14926878 100.0 %	
Minimum: Maximum:	-74.68634033203125 21.659942626953125	intensity_db intensity_db
Mean: Median: Std-Dev: Coefficient of Variation:	-13.497604982127445 -13.529031813144684 7.622196251455891 0.9633190730080097	intensity_db intensity_db intensity_db intensity_db

Figure 72 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

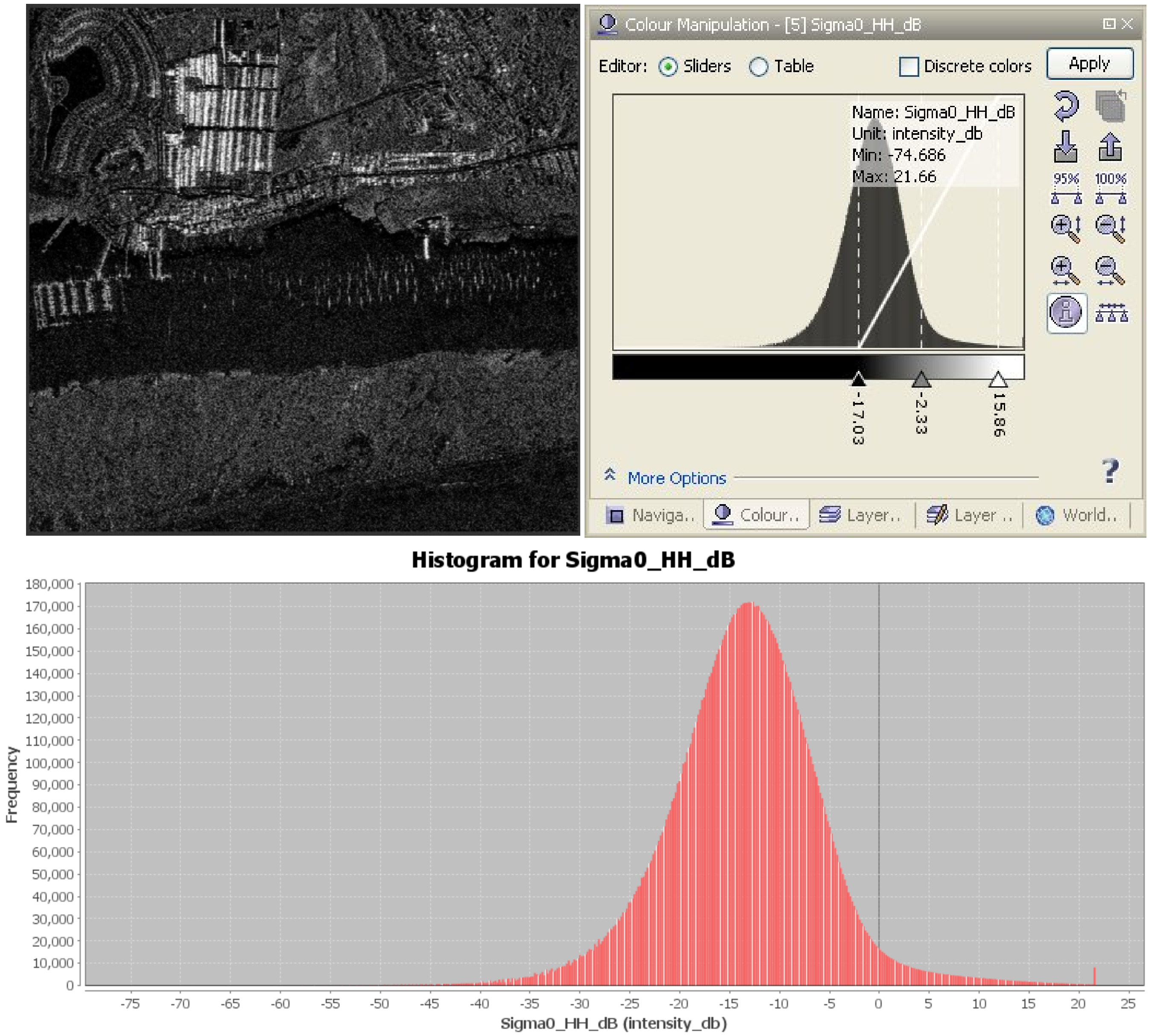


Figure 72 – Radarsat2-Spotlight, 14Dec.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 73, the maximum Sigma Naught values (σ°) of the targets are the following for each of the 3 sections in which the Image has been divided: Section 1 (in Green) about 9.0 dB, Section 2 (in yellow) about 12.9 dB , and Section 3 (in Red) about .13.4 dB.

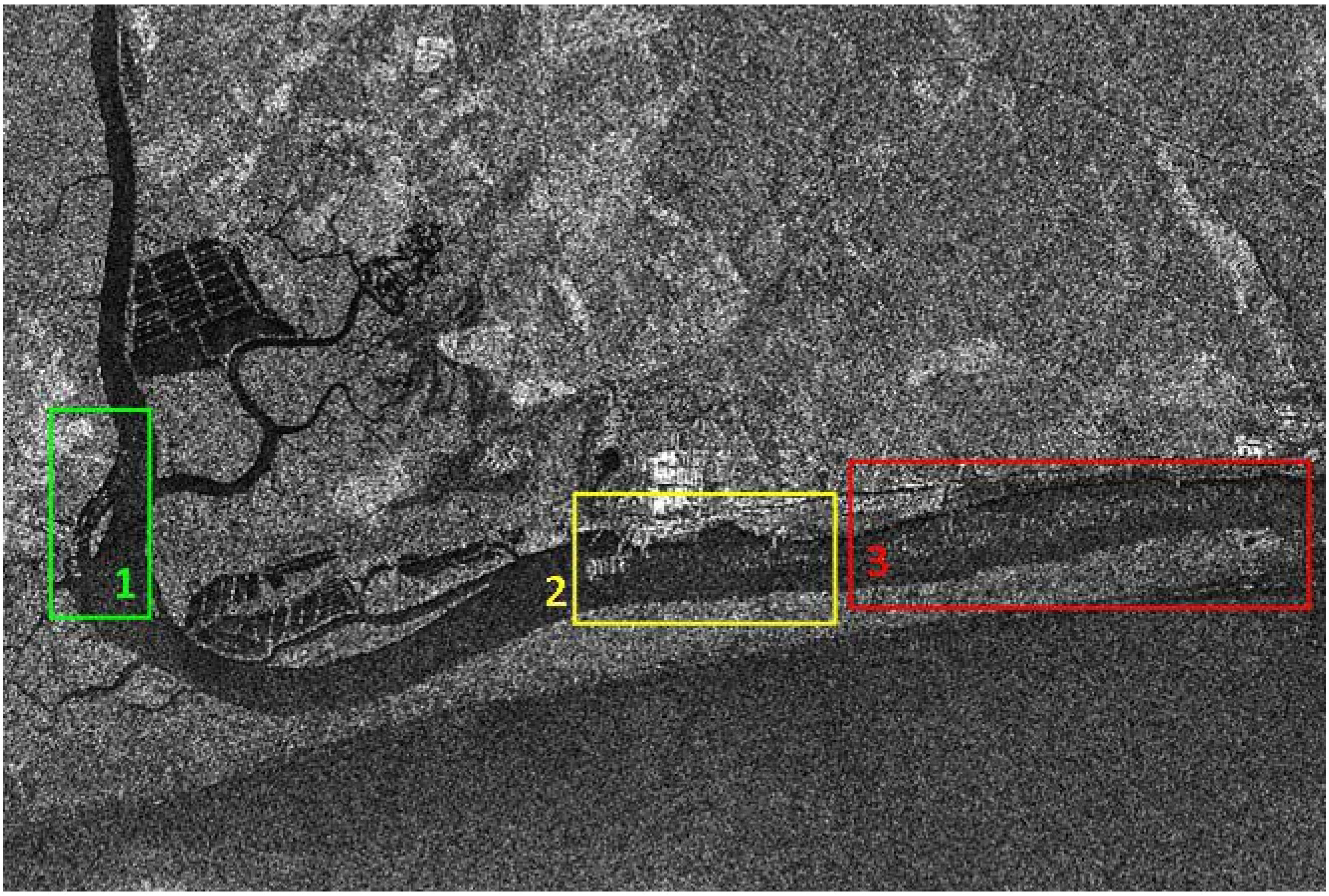


Figure 73 – Radarsat2-Spotlight, 14Dec.2010. In order to facilitate the analysis the image was divided in 3 sections: 1 (in Green), 2 (in yellow) and 3 (in red).

6.1.3 – TerraSAR-X - Spotlight,15Dec.2010(18:23h UTC), Sagres-Algarve

Figure 74 illustrates the Amplitude and Intensity bands of the TerraSAR-X - Spotlight image (15Dec.2010).

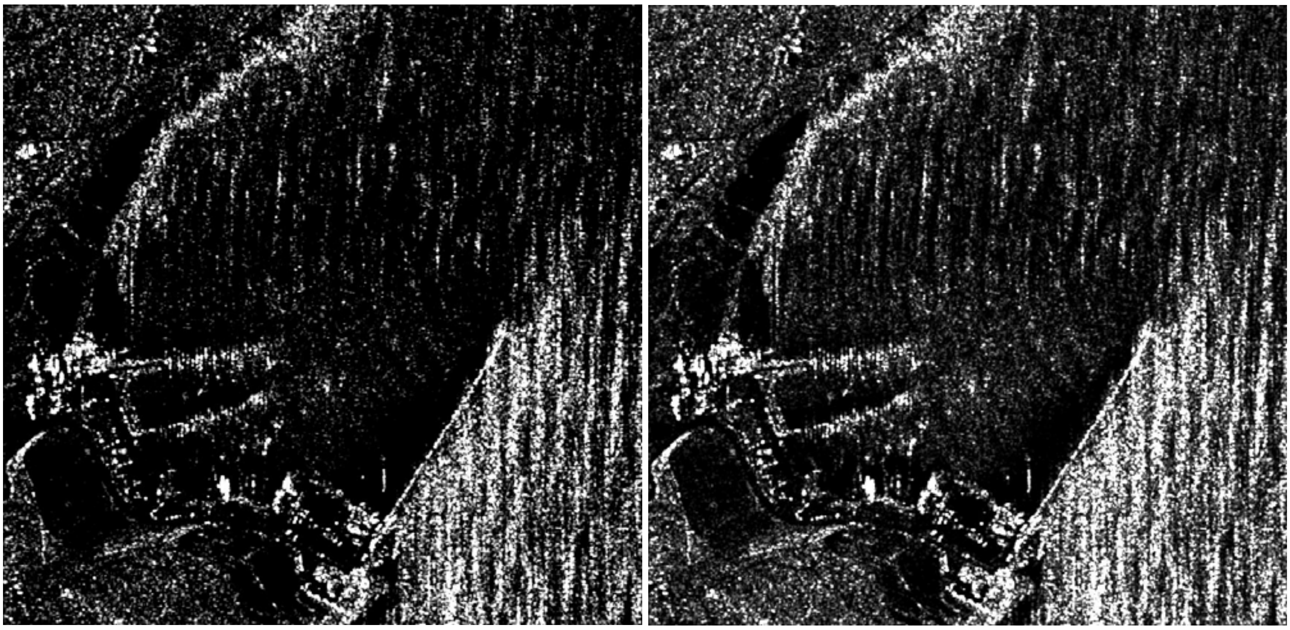


Figure 74 – TerraSAR-X – Spotlight, 15Dec.2010 - On the left, the Amplitude band. On the right the Intensity band.

Figure 75 illustrates the Sigma Naught Coefficient of the TerraSAR-X - Spotlight image (15Dec.2010) expressed in terms of intensity and decibel (dB).

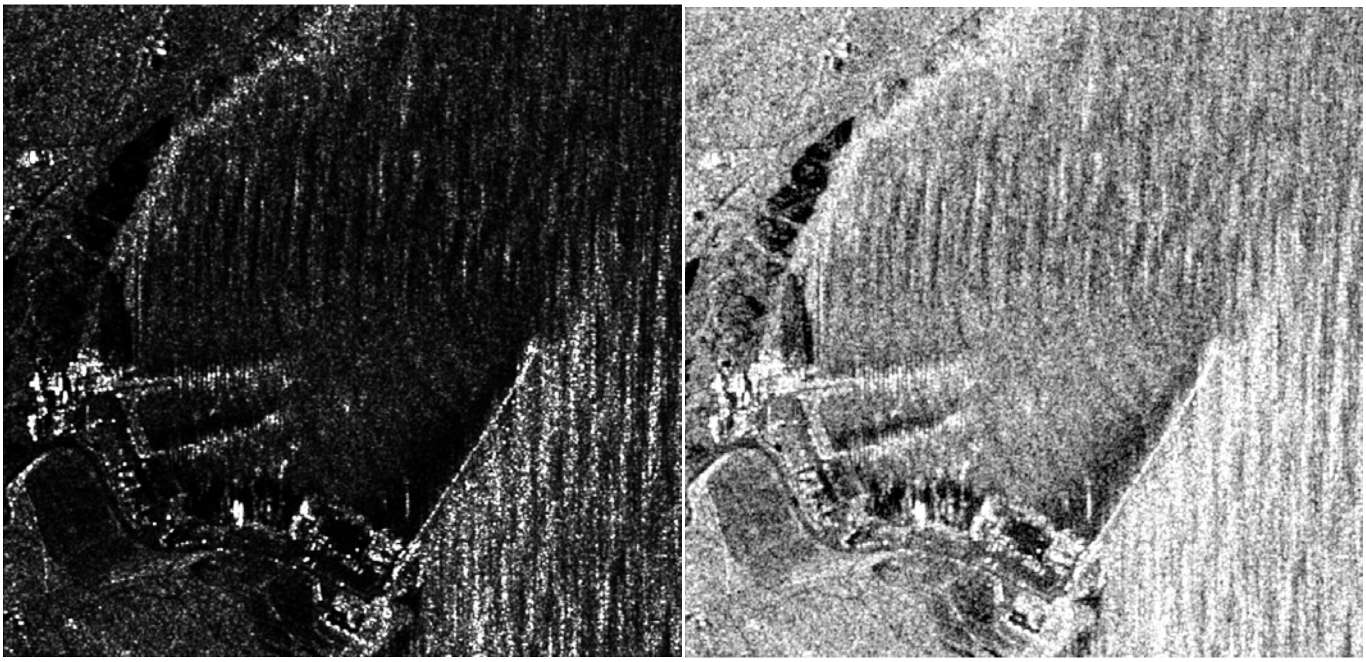


Figure 75 – TerraSAR-X – Spotlight, 15Dec.2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 76 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the TerraSAR-X - Spotlight image (15Dec.2010) expressed in dB.

Figure 76 – TerraSAR-X – Spotlight, 15Dec.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 77 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

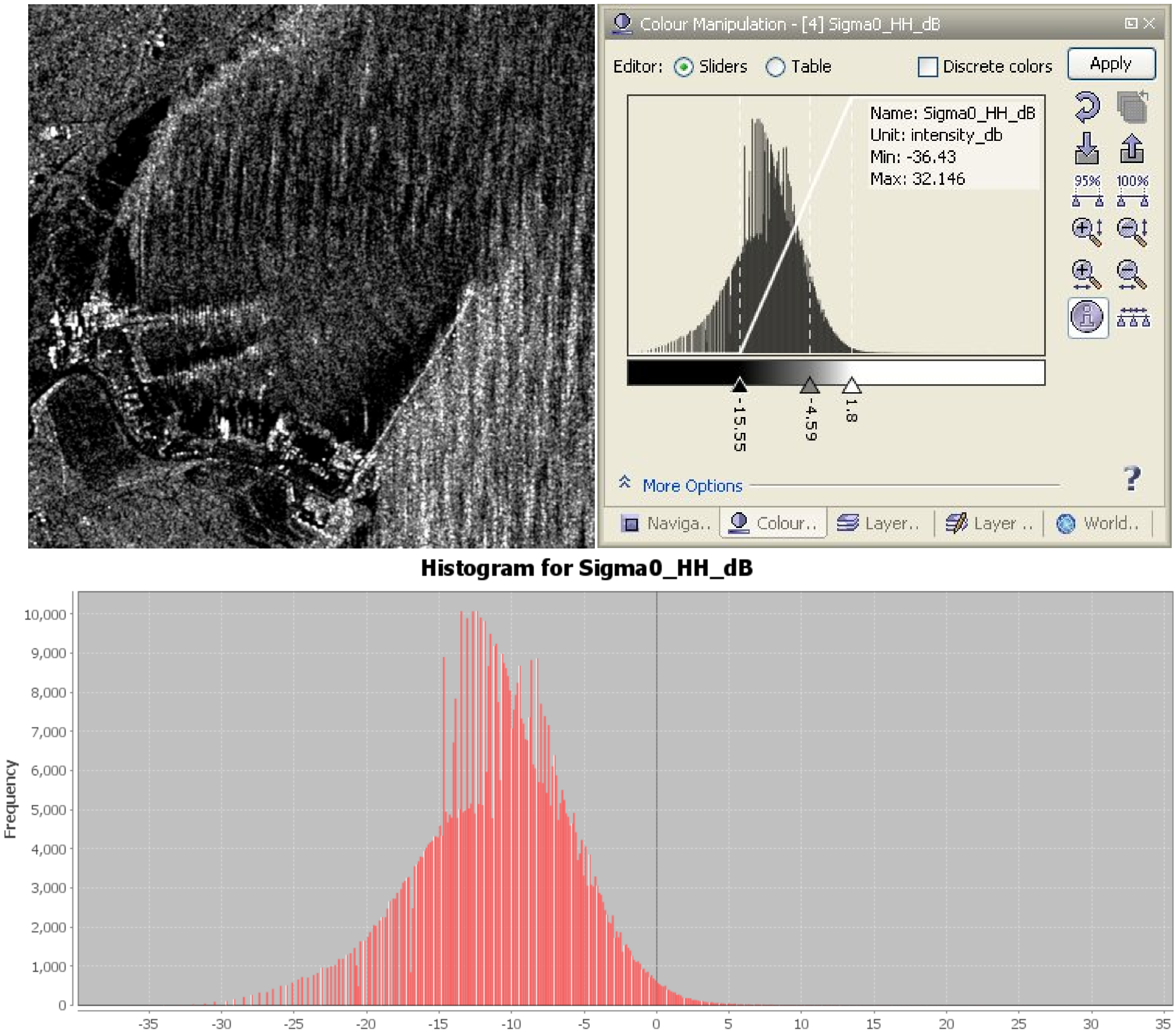


Figure 77 – TerraSAR-X – Spotlight, 15Dec.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 6 gives the statistics of the Sigma Naught (σ°) TerraSAR-X - Spotlight image (15Dec.2010). The Sigma Naught (σ°) range from -36.4 dB up to 32.1 dB. The Mean value is -10.7 dB, the Median is
-10.6 dB and the standard deviation is 4.9 dB.

Table 6– Statistics of the TerraSAR-X - Spotlight image 15Dec.2010 (18:23h UTC)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	691935	
Number of considered pixels:	691935	
Ratio of considered pixels:	100.0 %	
Minimum:	-36.4	intensity_db
Maximum:	32.1	intensity_db
Mean:	-10.7	intensity_db
Median:	-10.6	intensity_db
Std-Dev:	4.9	intensity_db
Coefficient of Variation:	0.8	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 75, the maximum Sigma Naught values (σ°) of the targets is 9.0 dB. Not all the targets of opportunity exhibit clear SAR signatures. The main reasons seem to be the sea state, wind speed.

6.1.4 – Rdarsat-2-Spotlight, 16Dec.2010 (18:36h UTC), Punta Umbria Spain

Figure 78 illustrates the Amplitude and Intensity bands of the Radarsat2-Spotlight image (16Dec.2010).

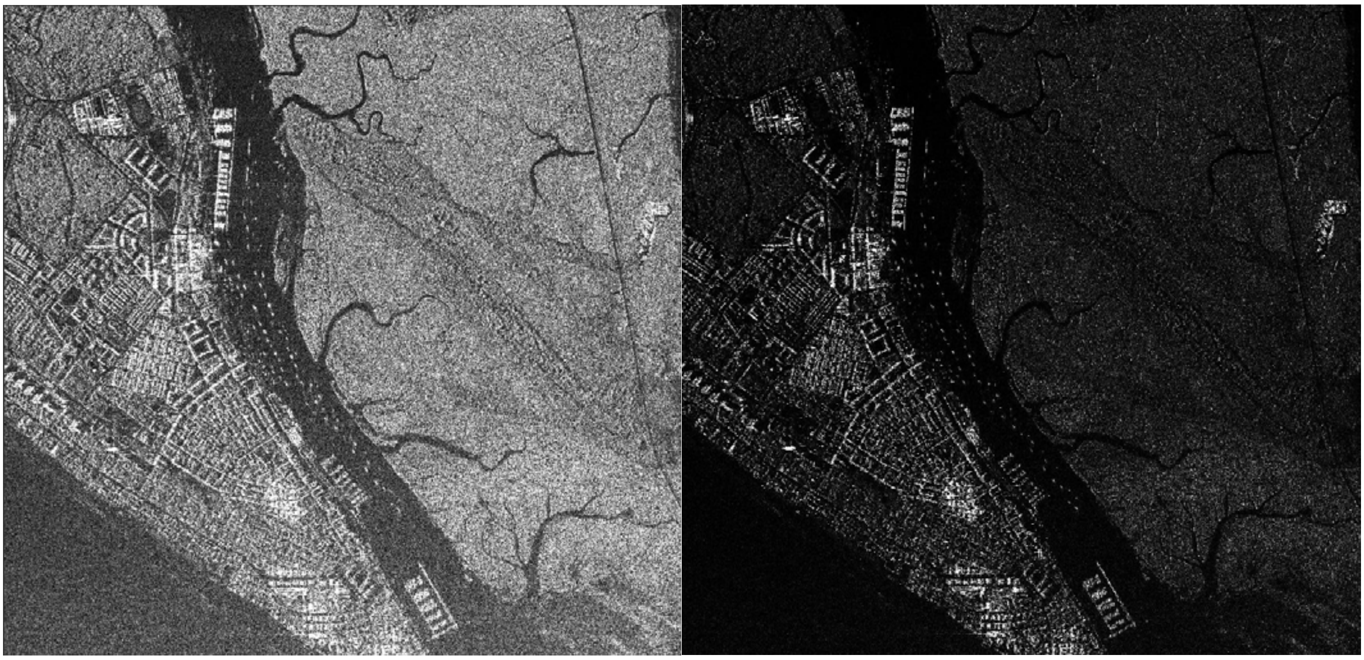


Figure 78 – Radarsat2-Spotlight , 16Dec.2010 - On the left, the Amplitude band. On the right the Intensity band.

Figure 79 illustrates the Sigma Naught Coefficient of the Radarsat2-Spotlight image (16Dec.2010) expressed in terms of intensity and decibel (dB).

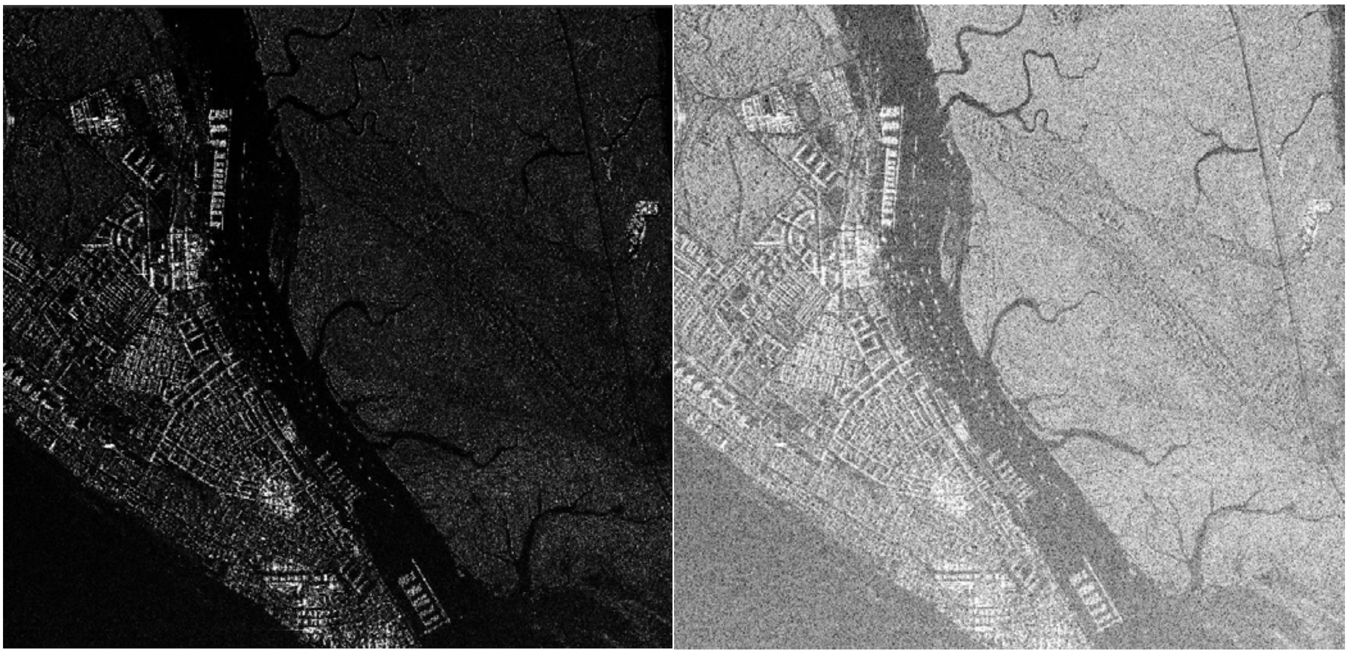


Figure 79 – Radarsat2-Spotlight, 16Dec.2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 80 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the Radarsat2-Spotlight image (16Dec.2010) expressed in dB.

Figure 80 – Radarsat2-Spotlight, 16Dec.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 81 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

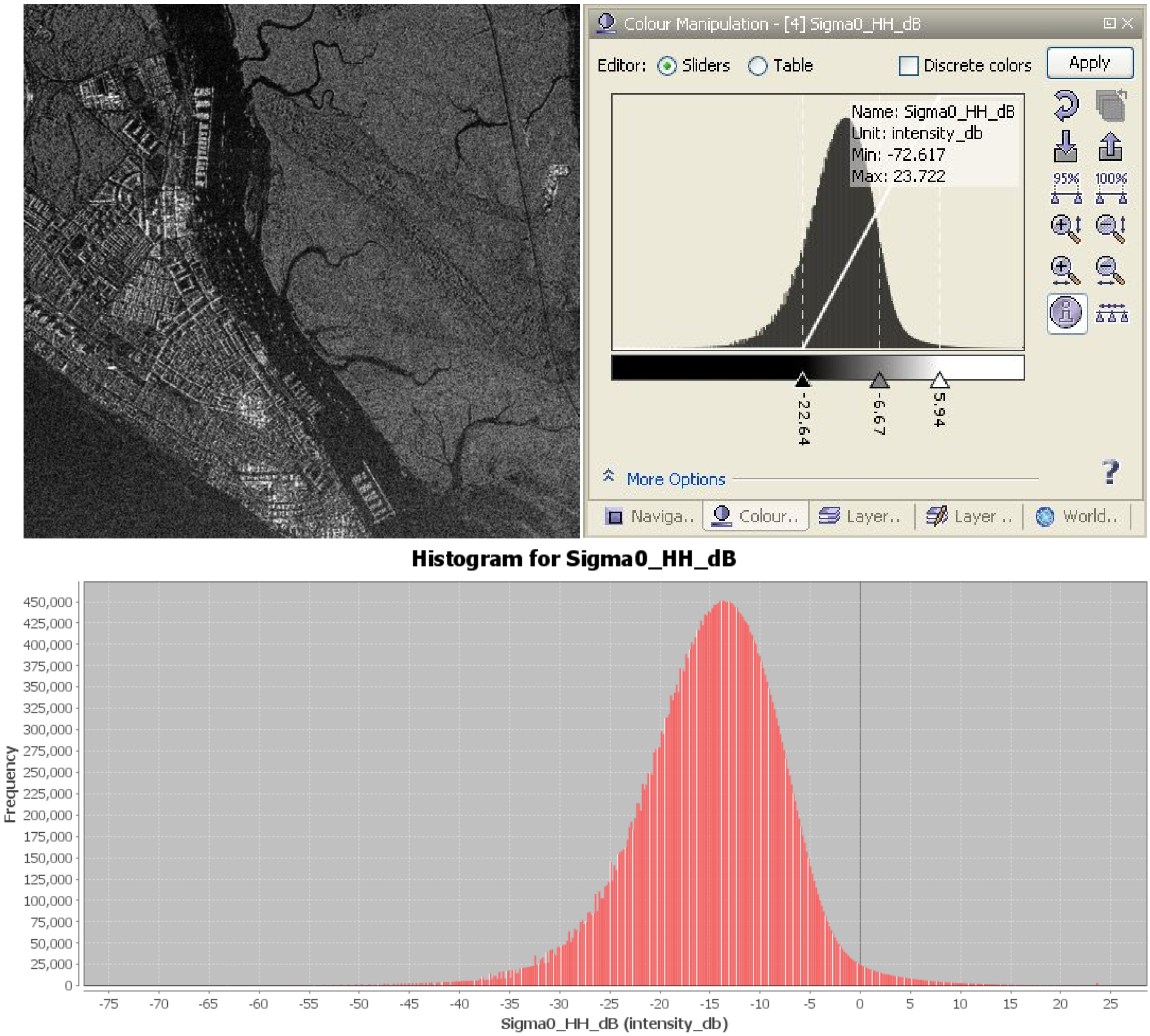


Figure 81 – Radarsat2-Spotlight, 16Dec.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 7 gives the statistics of the Sigma Naught (σ°) Radarsat2-Spotlight image (16Dec.2010). The Sigma Naught (σ°) range from -72.6 dB up to 23.7 dB. The Mean value is -14.9 dB, the Median is
-14.5 dB and the standard deviation is 7.2 dB.

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 81, the maximum Sigma Naught value (σ°) observed is about 9.0 dB.

Table 7– Statistics of the Radarsat2-Spotlight image 16Dec.2010 (18:37h UTC)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	39391256	
Number of considered pixels:	39391256	
Ratio of considered pixels:	100.0 %	
Minimum:	-72.6	intensity_db
Maximum:	23.7	intensity_db
Mean:	-14.9	intensity_db
Median:	-14.5	intensity_db
Std-Dev:	7.2	intensity_db
Coefficient of Variation:	0.9	intensity_db

6.1.5 – Radarsat2-Spotlight, 18Dec.2010 (06:23h UTC), Cadiz-Spain

Figure 82 illustrates the Amplitude and Intensity bands of the Radarsat2-Spotlight image (18Dec.2010).

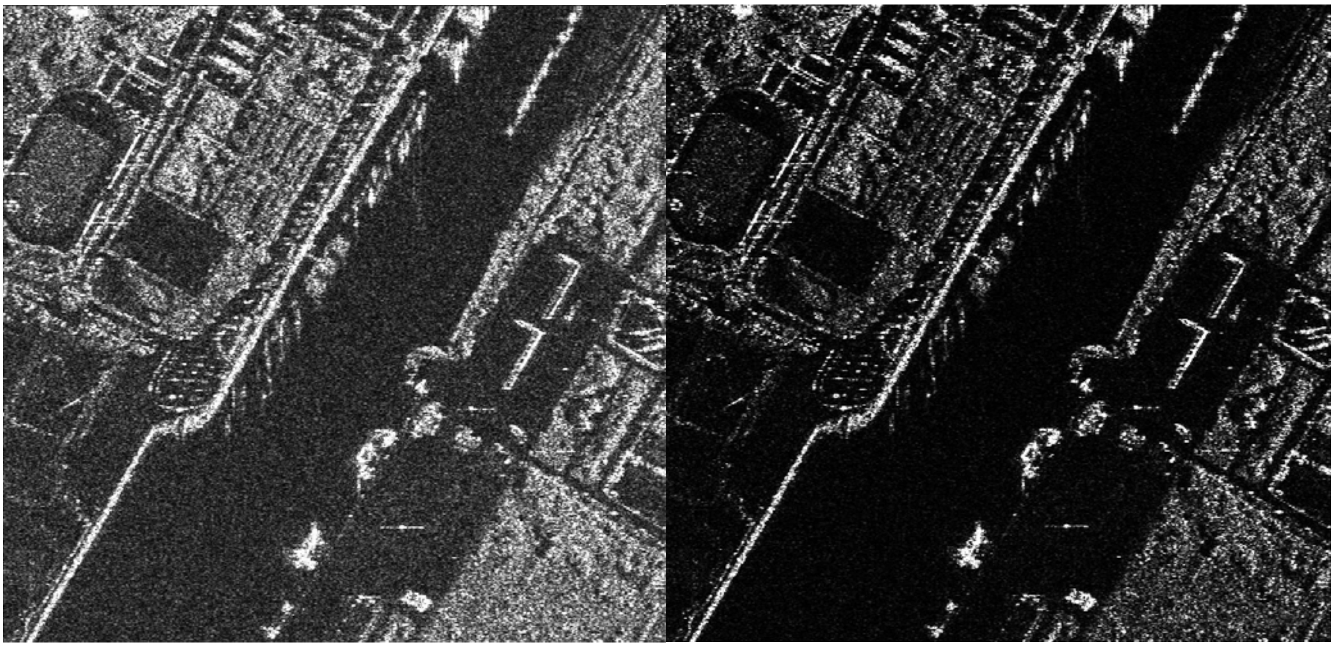


Figure 82 – Radarsat2-Spotlight, 18Dec.2010 - On the left, the Amplitude band. On the right the Intensity band.

Figure 83 illustrates the Sigma Naught Coefficient of the Radarsat2-Spotlight image (18Dec.2010) expressed in terms of intensity and decibel (dB).

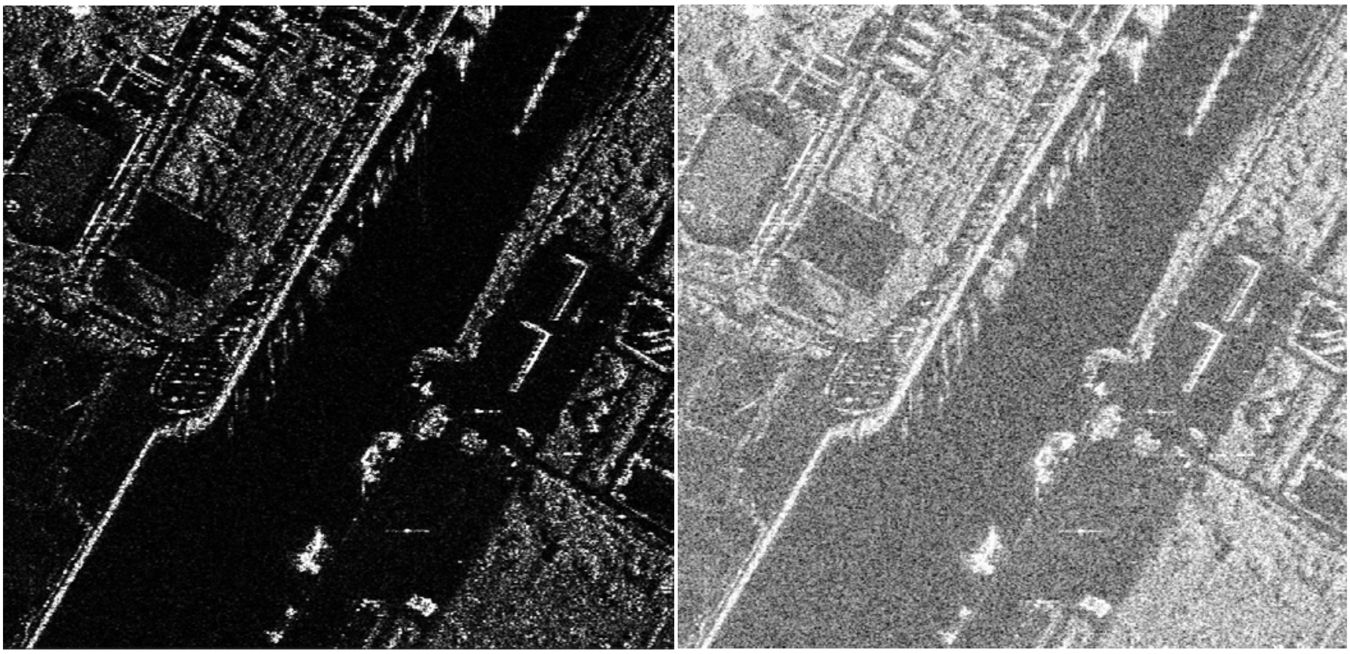


Figure 83 – Radarsat2-Spotlight, 18Dec.2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 84 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the Radarsat2-Spotlight image (18Dec.2010) expressed in dB.

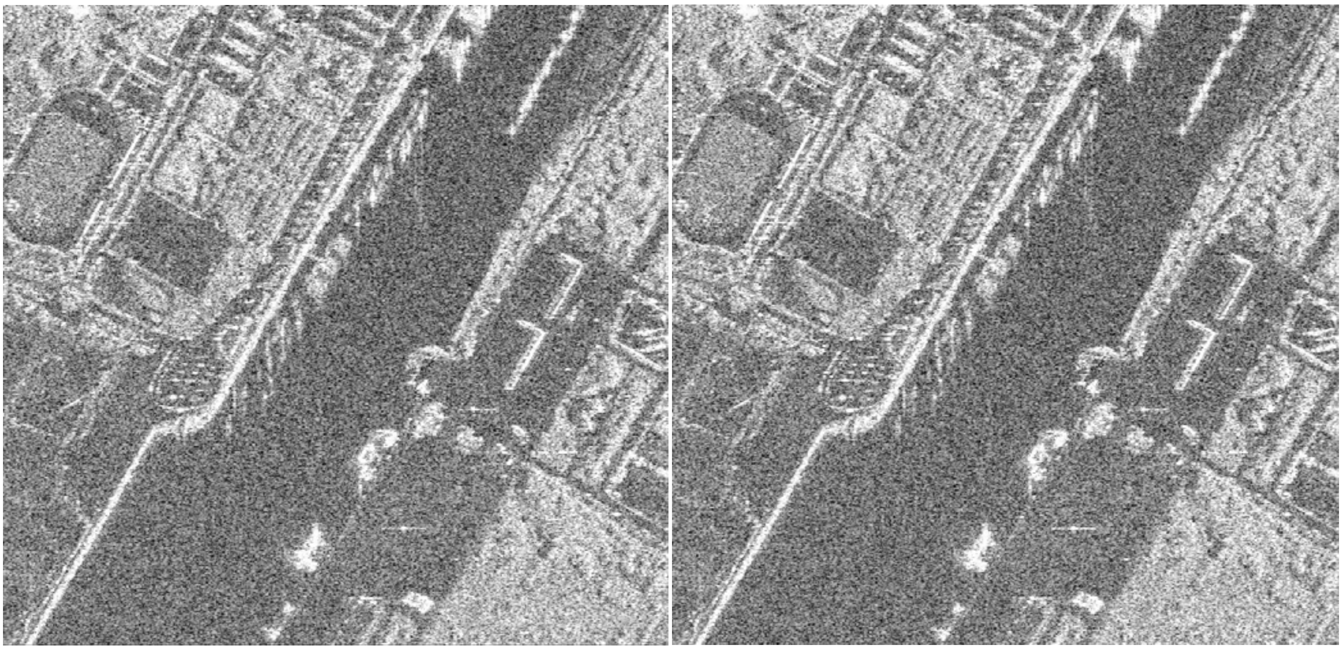


Figure 84 – Radarsat2-Spotlight, 18Dec.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 85 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

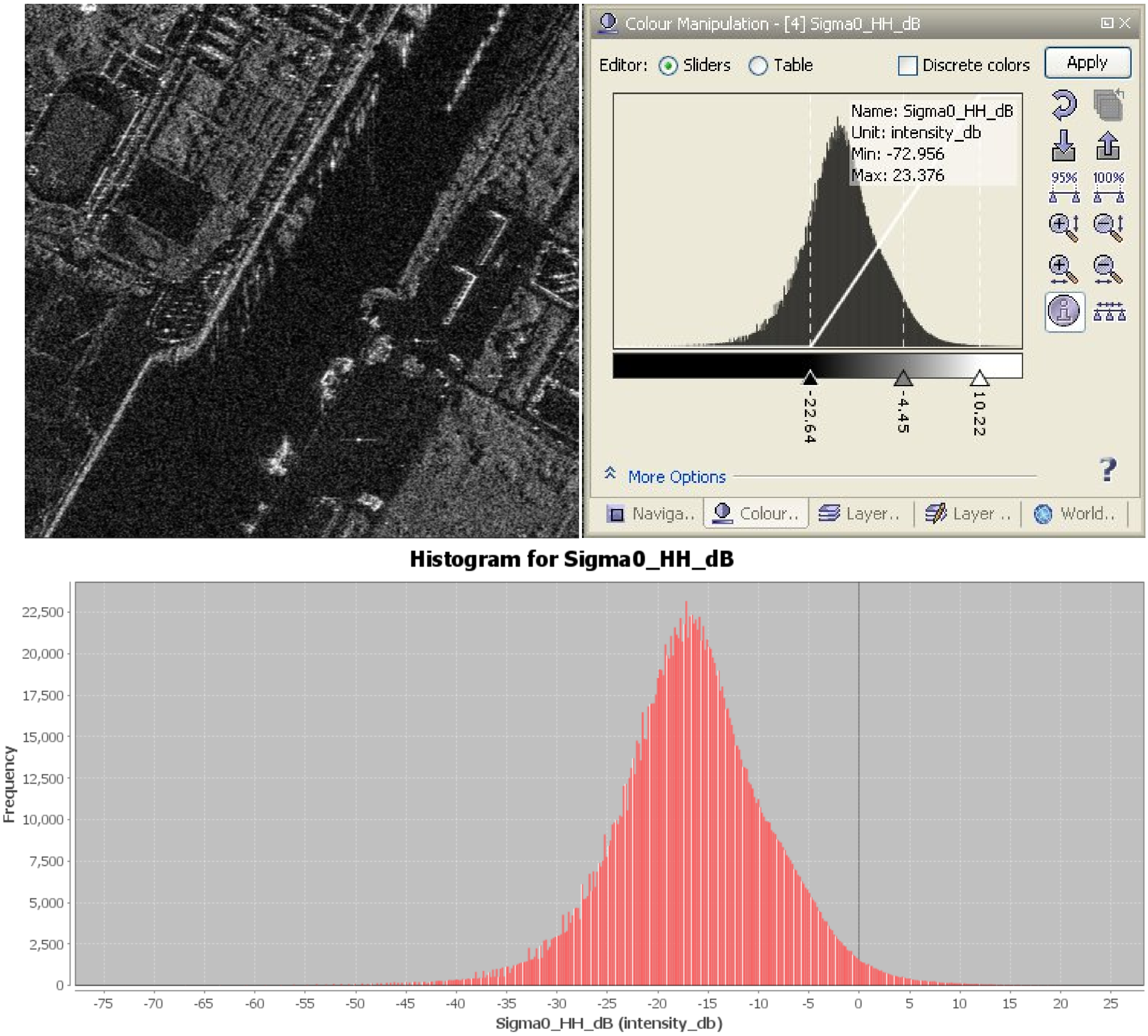


Figure 85 – Radarsat2-Spotlight, 18Dec.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 8 gives the statistics of the Sigma Naught (σ°) Radarsat2-Spotlight image (18Dec.2010). The Sigma Naught (σ°) range from -72.9 dB up to 23.4 dB. The Mean value is -16.5 dB, the Median is
-16.7 dB and the standard deviation is 7.6 dB.

Table 8– Statistics of the Radarsat2-Spotlight image 18Dec.2010 (06:23h UTC)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	1866566	
Number of considered pixels:	1866566	
Ratio of considered pixels:	100.0 %	
Minimum:	-73.0	intensity_db
Maximum:	23.4	intensity_db
Mean:	-16.5	intensity_db
Median:	-16.7	intensity_db
Std-Dev:	7.6	intensity_db
Coefficient of Variation:	0.8	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 85, the maximum Sigma Naught value (σ°) observed in the subset analysed is about 15.7 dB.

6.1.6 – Radarsat2-Spotlight, 23Dec.2010 (18:33h UTC), Isla Cristina

Figure 86 illustrates the Amplitude and Intensity bands of the Radarsat2-Spotlight image (23Dec.2010).

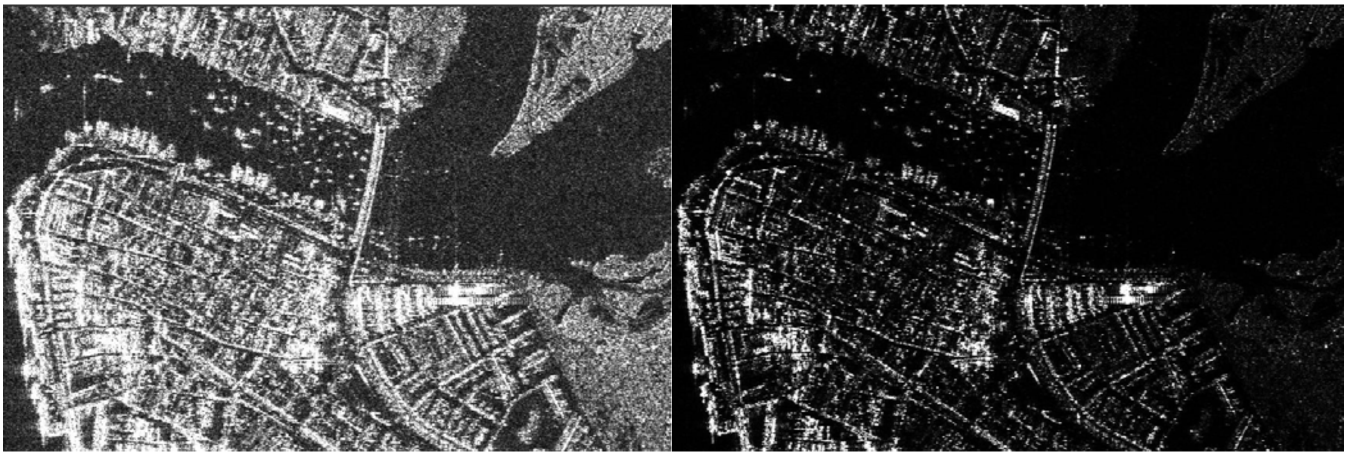


Figure 86 – Radarsat2-Spotlight, 23Dec.2010 - On the left, the Amplitude band. On the right the Intensity band.

Figure 87 illustrates the Sigma Naught Coefficient of the Radarsat2- Spotlight image (23Dec.2010) expressed in terms of intensity and decibel (dB).

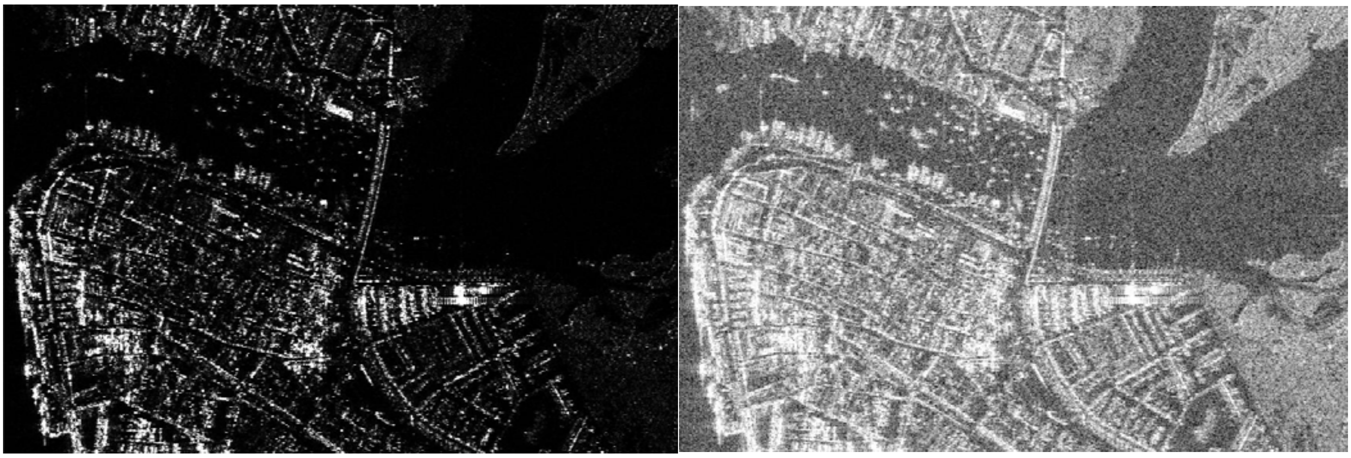


Figure 87–Radarsat2- Spotlight, 23Dec.2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 88 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the Radarsat2- Ultrafine image (21Dec.2009) expressed in dB.

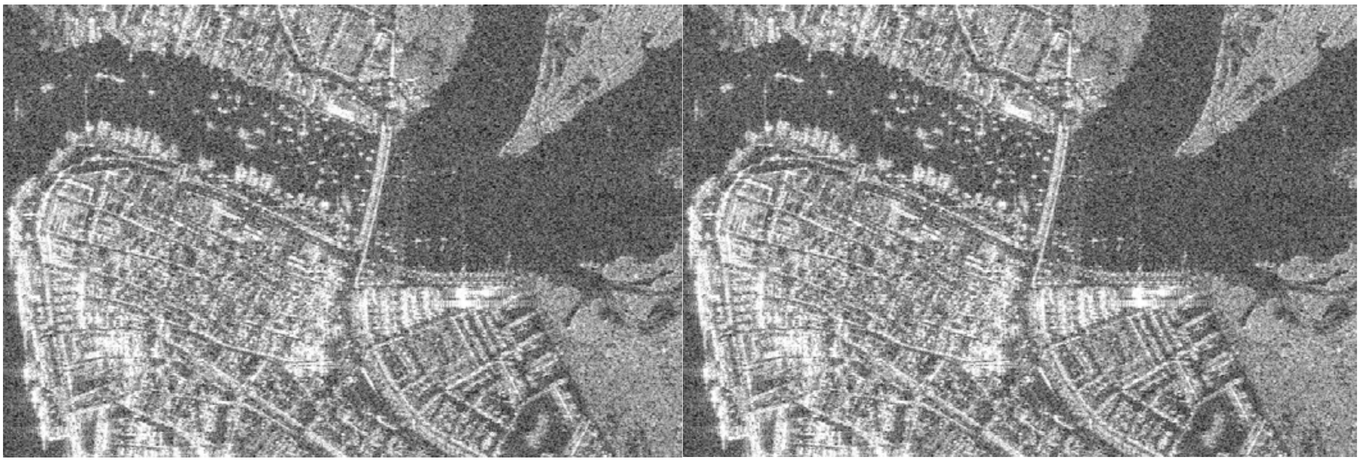


Figure 88 – RadarSAt2- Spotlight, 23Dec.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 89 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

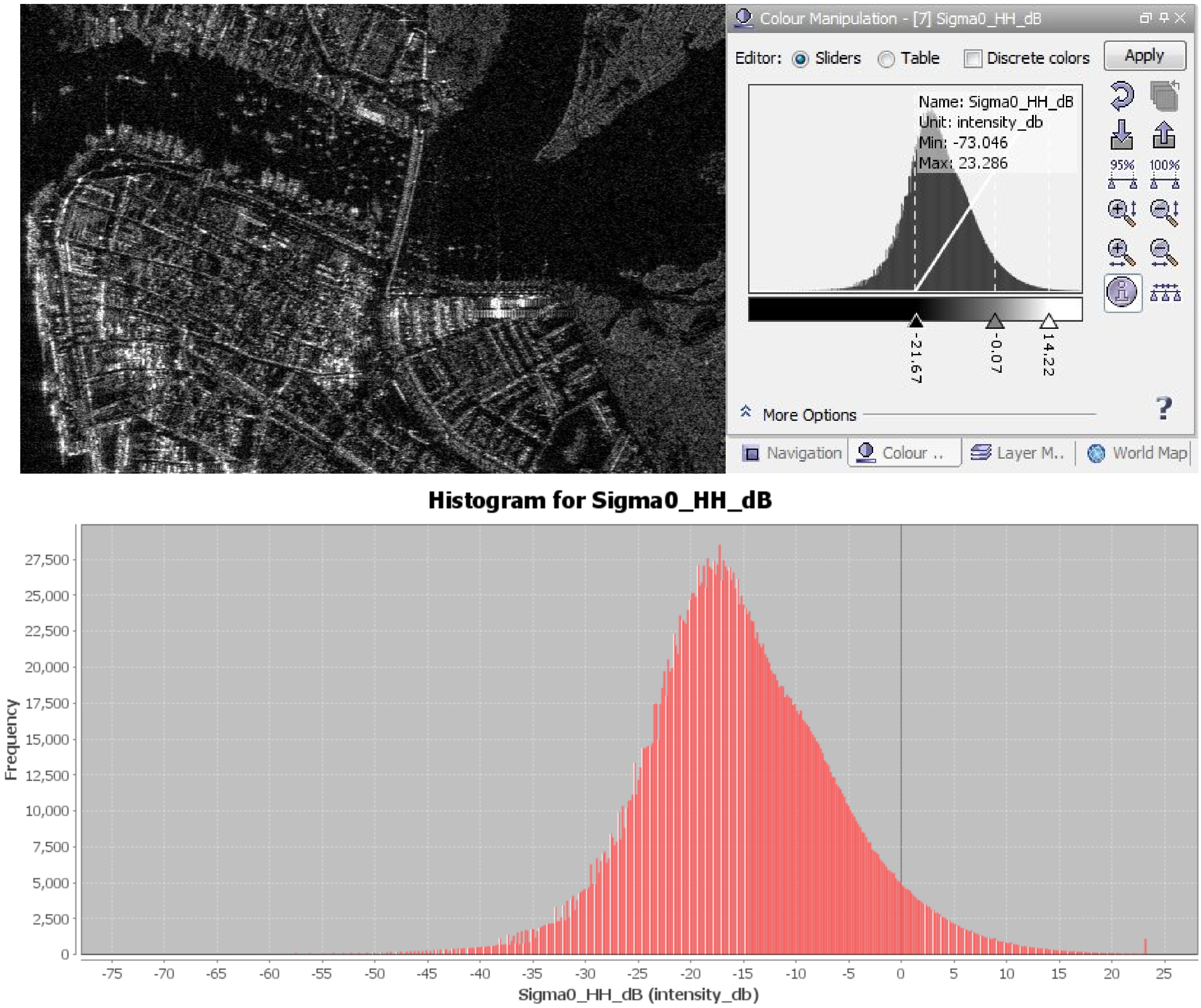


Figure 89 – Radarsat2 – Spotlight 23Dec.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

Table 9 gives the statistics of the Sigma Naught (σ°) Radarsat2- Ultrafine image (23Dec.2010). The Sigma Naught (σ°) range from -73.0 dB up to 23.3 dB. The Mean value is -15.3 dB, the Median is
-15.9 dB and the standard deviation is 9.0 dB.

Table 9 – Statistics of the Radarsat2- Spotlight image 23Dec.2010 (18:33h UTC)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	2775079	
Number of considered pixels:	2775079	
Ratio of considered pixels:	100.0 %	
Minimum:	-73.0	intensity_db
Maximum:	23.3	intensity_db
Mean:	-15.3	intensity_db
Median:	-16.0	intensity_db
Std-Dev:	9.0	intensity_db

Coefficient of Variation:	-0.6	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 89, the maximum Sigma Naught value (σ°) observed in the subset analysed is about 9.8 dB.

6.1.7 – TerraSAR-X-Spotlight, 24Dec.2010 (06:46:40h UTC), Cascais

Figure 90 illustrates the Amplitude and Intensity bands of the TerraSAR-X-Spotlight image (24Dec.2010).

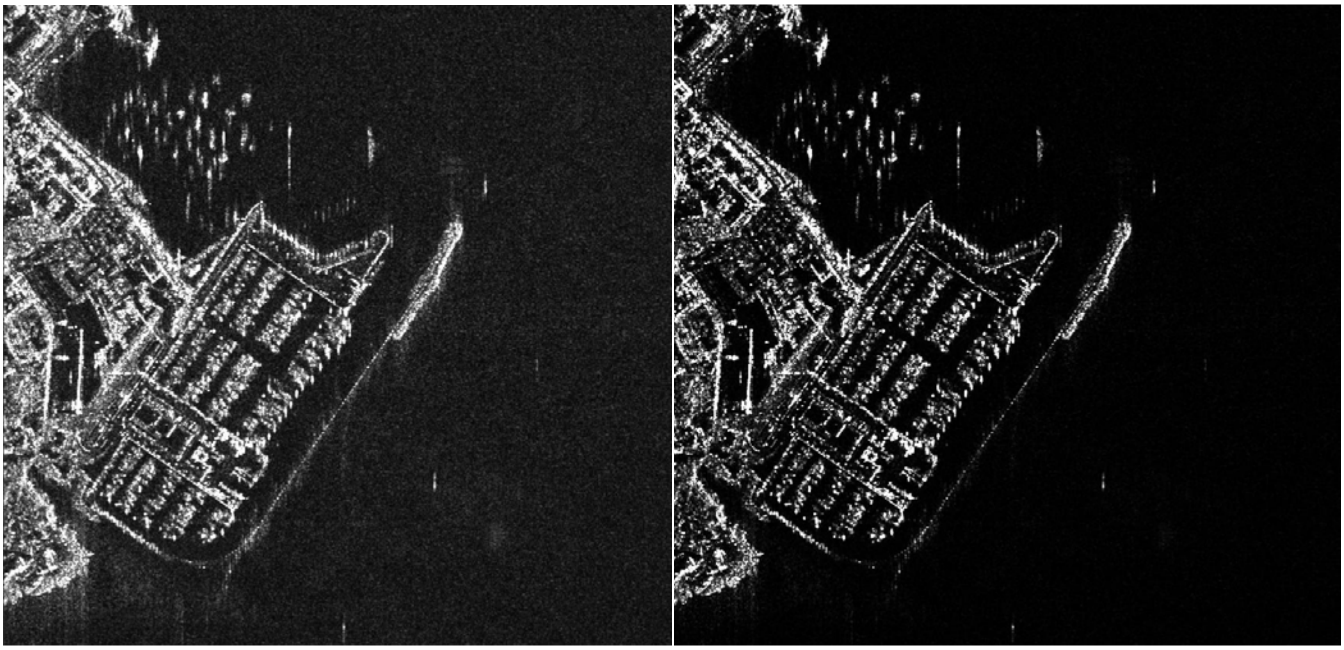


Figure 90 – TerraSAR-X-Spotlight, 24Dec.2010 - On the left, the Amplitude band. On the right the Intensity band.

Figure 91 illustrates the Sigma Naught Coefficient of the TerraSAR-X-Spotlight image (24Dec.2010) expressed in terms of intensity and decibel (dB).

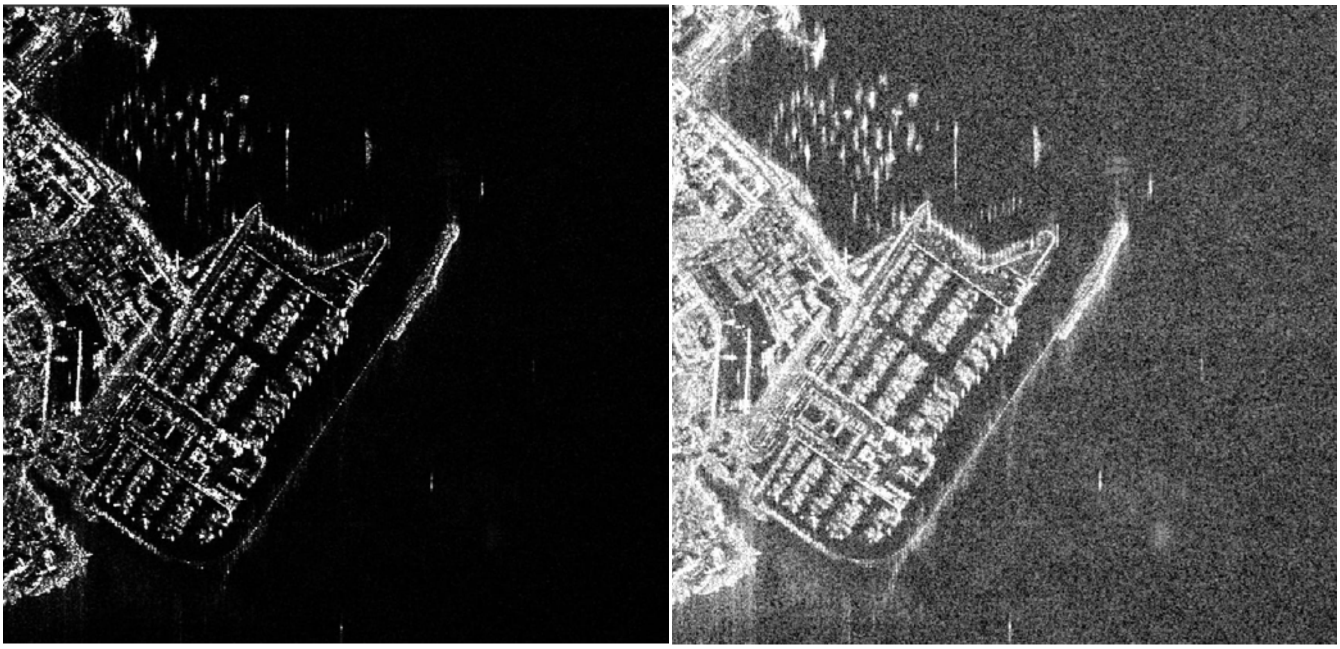


Figure 91– TerraSAR-X-Spotlight, 24Dec.2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 92 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the TerraSAR-X-Spotlight image (24Dec.2010) expressed in dB.

Figure 92 – TerraSAR-X-Spotlight, 24Dec.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 93 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

Table 10 gives the statistics of the Sigma Naught (σ°) TerraSAR-X-Spotlight image (24Dec.2009). The Sigma Naught (σ°) range from -39.9 dB up to 28.9 dB. The Mean value is -19.2 dB, the Median is
-20.8 dB and the standard deviation is 6.8 dB.

Table 10 – Statistics of the TerraSAR-X-Spotlight image 24Dec.2010 (06:46:40h UTC)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	1743018	
Number of considered pixels:	1743018	
Ratio of considered pixels:	100.0 %	
Minimum:	-40.0	intensity_db
Maximum:	29.0	intensity_db
Mean:	-19.2	intensity_db
Median:	-20.8	intensity_db
Std-Dev:	6.8	intensity_db
Coefficient of Variation:	0.5	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 93, the maximum Sigma Naught value (σ°) observed in the subset analysed is about 11.8 dB.

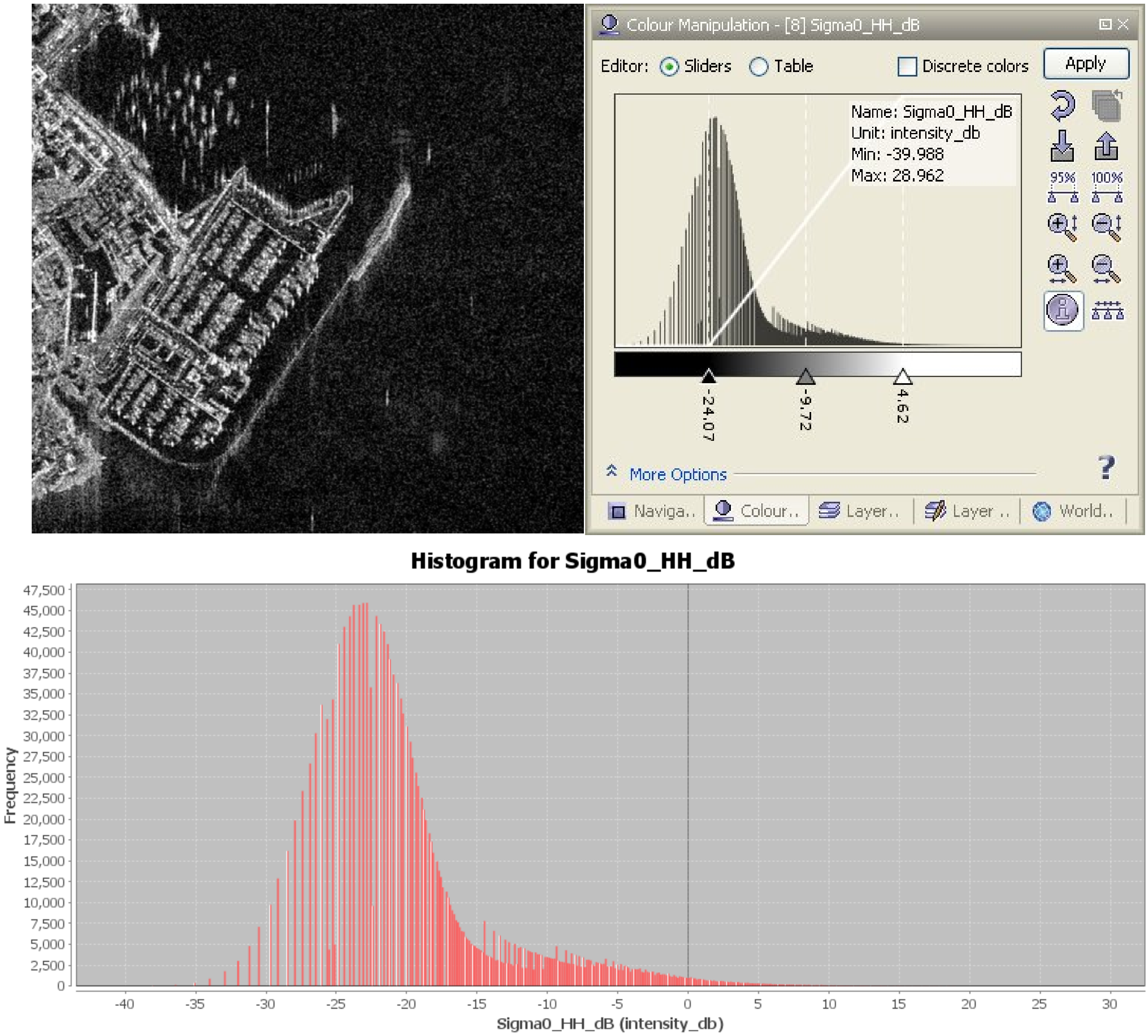


Figure 93 – TerraSAR-X-Spotlight 24Dec.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

6.1.8 – Radarsat-2-Ultrafine, 24Dec.2010 (06:47:26h UTC), Cascais

Figure 94 illustrates the Amplitude and Intensity bands of the Radarsat-2-Ultrafine image (24Dec.2010).

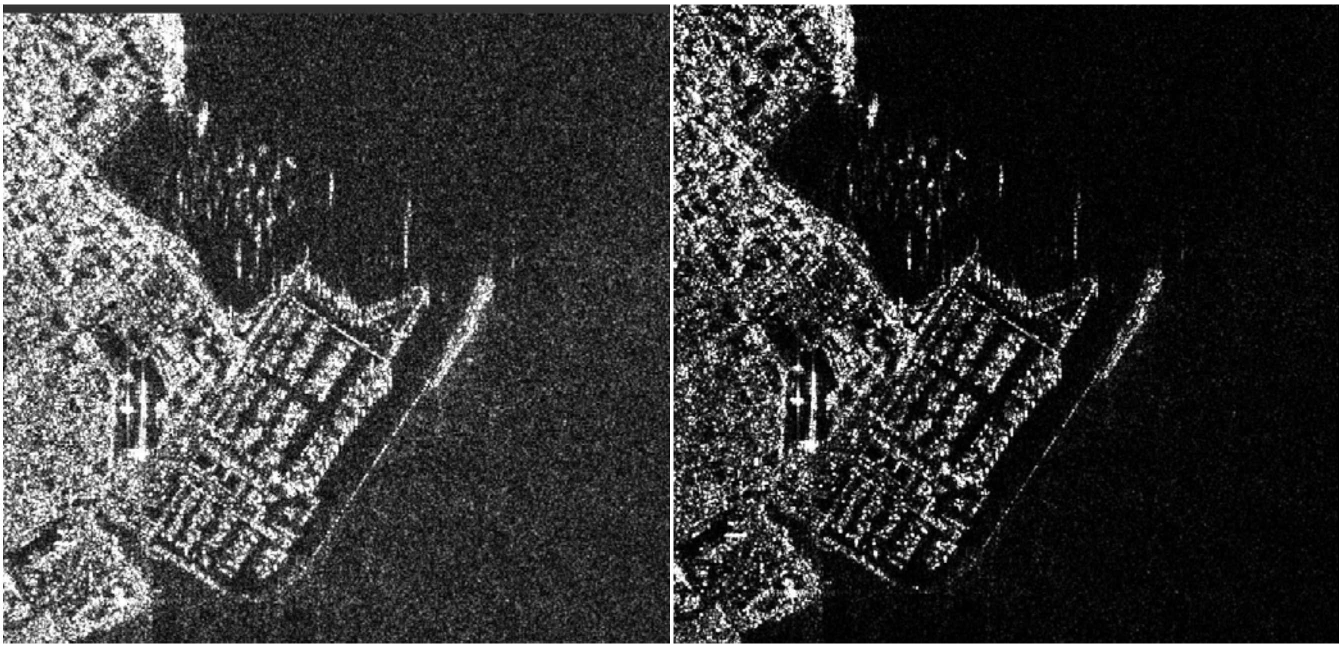


Figure 94 – Radarsat-2-Ultrafine, 24Dec.2010 - On the left, the Amplitude band. On the right the Intensity band.

Figure 95 illustrates the Sigma Naught Coefficient of the Radarsat-2-Ultrafine image (24Dec.2010) expressed in terms of intensity and decibel (dB).

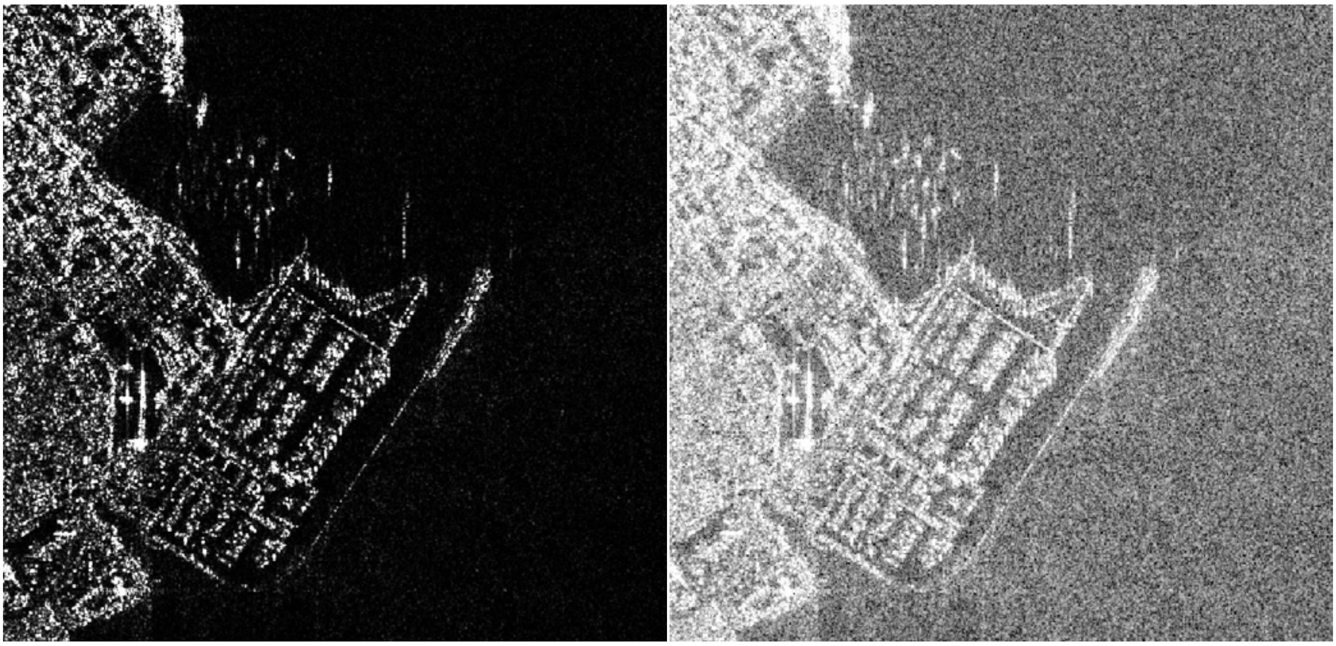


Figure 95– Radarsat-2-Ultrafine, 24Dec.2010 - On the left, the Sigma Naught (σ°) (intensity) and on the right, the Sigma Naught (σ°) (dB).

Figure 96 illustrates the Radar Brightness (Beta Naught (β°)), and the radiometric normalisation (Gamma Naught (γ°)) of the Radarsat-2-Ultrafine image (24Dec.2010) expressed in dB.

Figure 96 – Radarsat-2-Ultrafine, 24Dec.2010 - On the left, the Beta Naught (β°) and on the right, the Gamma Naught (γ°) (dB).

Figure 97 shows the Sigma Naught (σ°) in dB after colour manipulation and the histogram of the Sigma Naught (σ°) image.

Table 11 gives the statistics of the Sigma Naught (σ°) Radarsat-2-Ultrafine image (24Dec.2009). The Sigma Naught (σ°) range from -76.0 dB up to 10.7 dB. The Mean value is -17.0 dB, the Median is -17.6 dB and the standard deviation is 7.9 dB.

Table 11 – Statistics of the Radarsat-2-Ultrafine image 24Dec.2010 (06:46:40h UTC)

Statistics	Values	Unit
Only ROI-Mask pixels considered:	No	
Number of pixels total:	464260	
Number of considered pixels:	464260	
Ratio of considered pixels:	100.0 %	
Minimum:	-76.0	intensity_db
Maximum:	10.7	intensity_db
Mean:	-17.0	intensity_db
Median:	-17.6	intensity_db
Std-Dev:	8.0	intensity_db
Coefficient of Variation:	0.8	intensity_db

Checking the radar backscattering coefficient of the targets (small boats) detected in Figure 97, the maximum Sigma Naught value (σ°) observed in the subset analysed is about 8.4 dB.

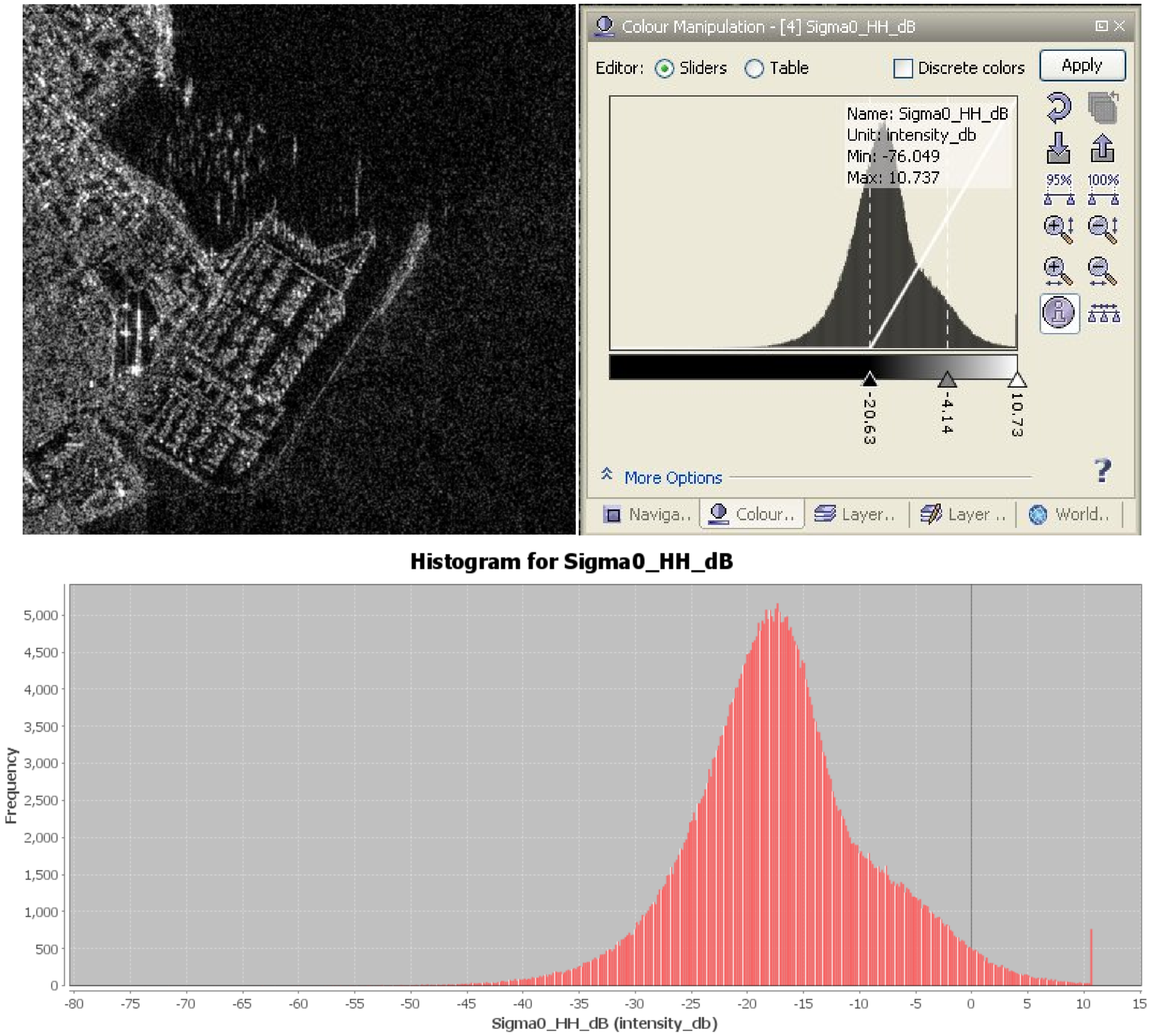


Figure 97 – Radarsat-2-Ultrafine, 24Dec.2010 - On the top left the Sigma Naught (σ°) after colour manipulation to enhance the targets and on the top right, the corresponding histogram. On the bottom, the histogram of the image.

6.2 – Small Boat Detection in SAR Satellite Imagery

This spaceborne SAR Small Boat detection experiment was performed with the following objectives:

- To assess the feasibility of detection of Small Boats in Synthetic Aperture Radar (SAR) Satellite imagery (Radarsat2 and TerraSAR-X), in particular on inland sea waters and Coastal Waters (e.g. Ports or Bays).

- To try to characterise the SAR signature of Small Boats in SAR Satellite imagery.

- To identify the limitations of current State-of-the-Art SAR Satellite technology for maritime surveillance, in particular for Small Boat detection.

Using spaceborne SAR for small boat detection is a challenging task because it is a complex problem, which involves several variables, such as the sea state, the wind speed, the incidence angle, the resolution, the image mode, the polarisation, the bands used, the type, shape and materials of the boat, etc.

The results of this small boat detection experiment on inland sea waters and coastal waters show that under suitable conditions of sea state, wind speed and incidence angle it is possible to detect small boats on inland sea waters and on coastal waters using spaceborne SAR images. In all eight spaceborne SAR images acquired during this experiment it was possible to detect small boats on inland sea waters and on coastal waters. However, several difficulties were identified, namely:

1.- It is difficult to estimate the empirical probability of detection. In order to be able to estimate an improved empirical probability of detection, a significant number of experiments under different conditions (e.g. sea state, wind speed, incidence angles, polarisations, different bands, different modes, weather, etc.) are required.

2.- The sea state, the wind speed and the incidence angle play a very important role in spaceborne SAR small boat detection. For instance, the difference between the SAR image acquired on 15 Dec. 2010 over Sagres (Algarve-Portugal) and the SAR images acquired over Cascais (Lisbon-Portugal) on 24 Dec. 2010 illustrate that role to some extent. In the first case the sea state was rougher and the wind speed higher than in the second case. In both cases the number of small boats available and used as targets of opportunity was similar. Despite of that, the number of small boats detected and the contrast of the SAR signatures was higher in the second case (Cascais) than in the first case (Sagres). This is illustrated in Figures 98 and 99. The Spaceborne SAR images were from the same Satellite (TerraSAR-X) and the mode was the same (Spotlight). The wave height and the wind speed were higher in Sagres than in Cascais and the incidence angle was higher in Cascais. Table 12 summarises these parameters.

Table 12 – Wave height, wind speed and incidence angle for Sagres (15Dec.2010) and Cascais (24Dec.2010).

	Wave Height	Wind Speed	Incidence Angle
Sagres-Algarve-Portugal	0.5 – 1m	1-5m/s	25deg
Cascais-Lisbon-Portugal	0.0-0.2m	0.3-2m/s	35deg

In order to better understand the correlation between the sea states, the wind speed, the incidence angle and other parameters to be able to estimate an empirical probability of detection a significant number of experiments under different conditions and scenarios is needed.

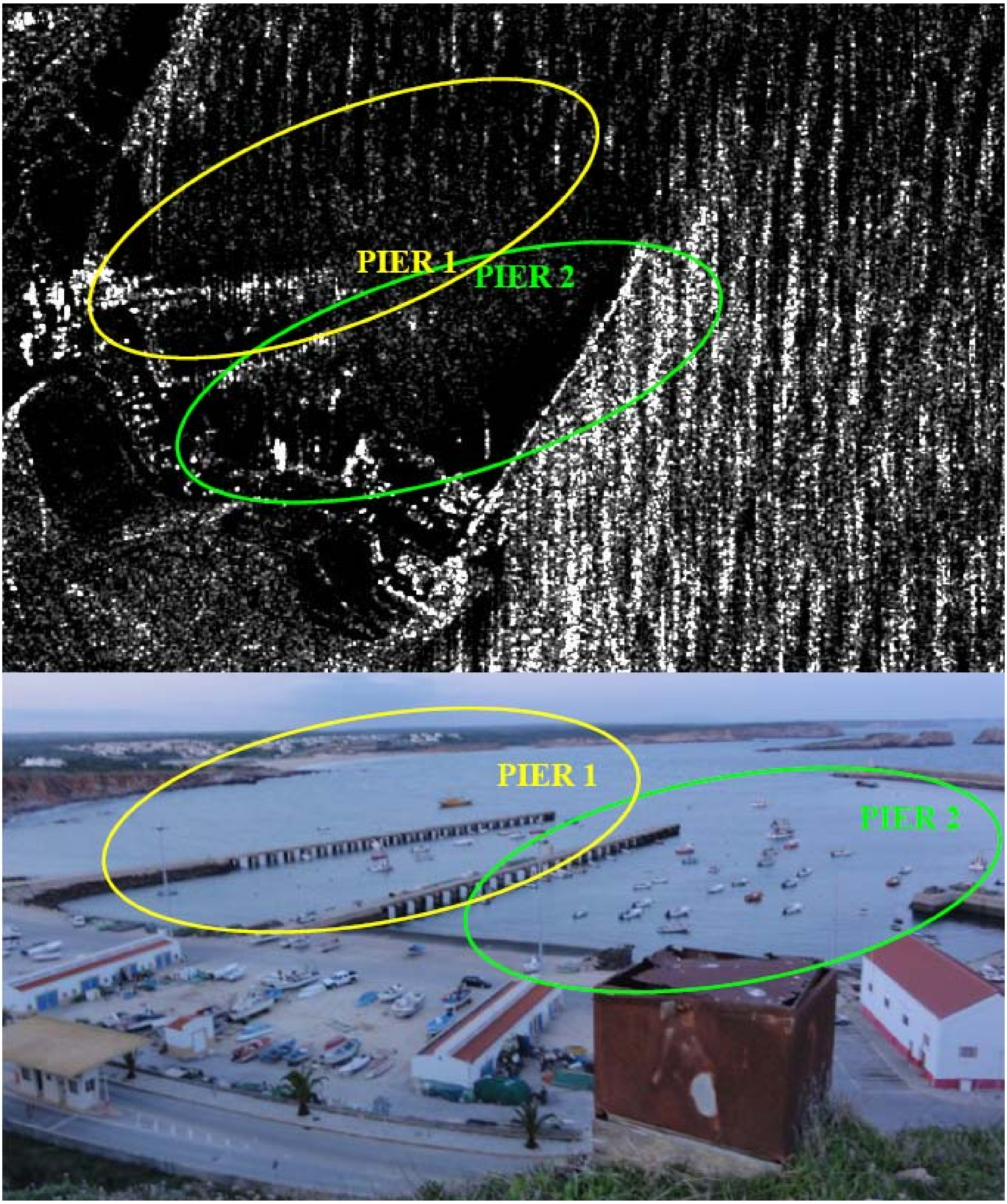


Figure 98 – TerraSAR-X-Spotlight, 15 Dec. 2010, Sagres-Portugal. The sea was not flat with wave height in the range of 0.5-1m) and the wind speed in the range of 3-5m/s. The incidence angle was about 25deg.

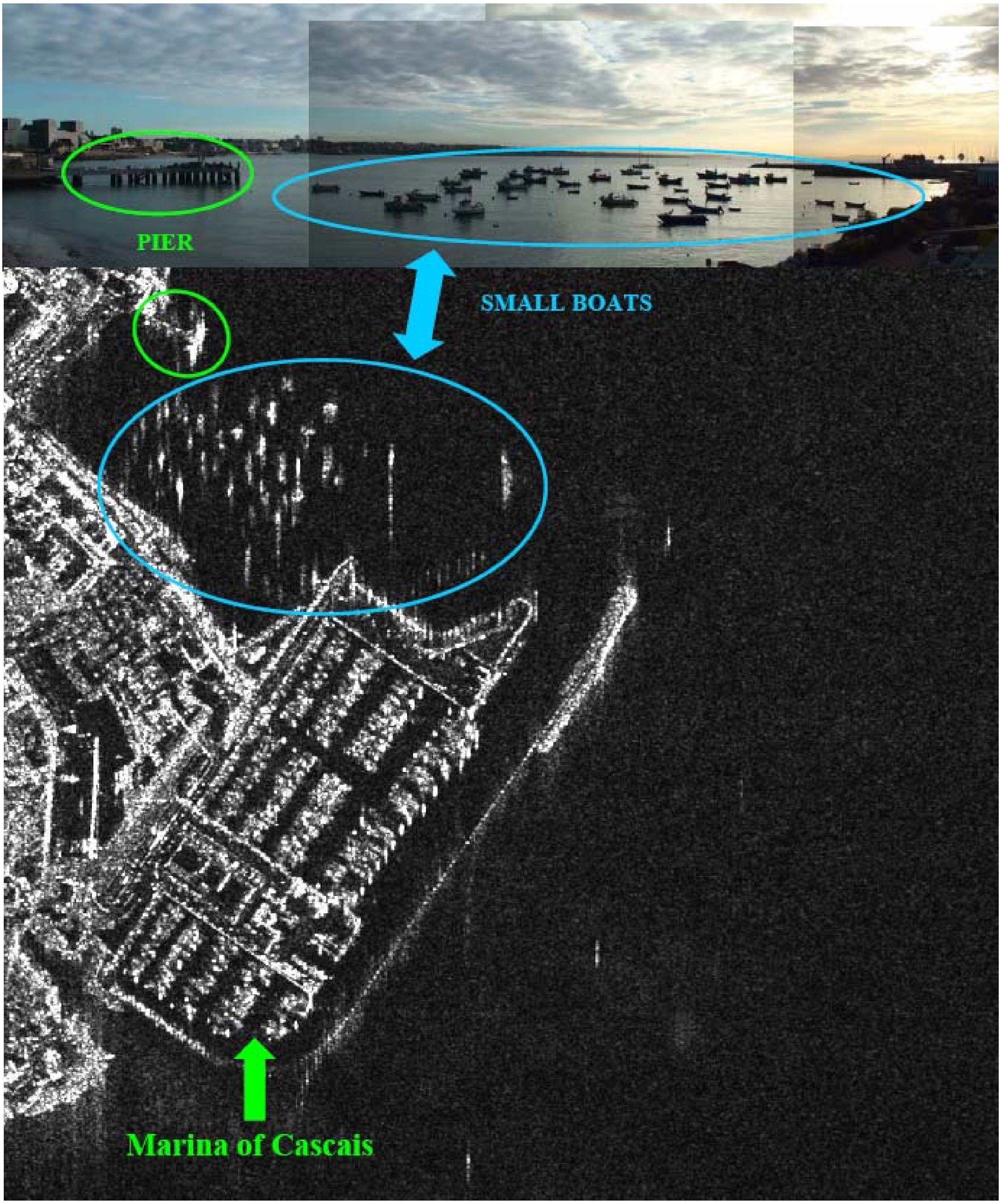


Figure 99 – TerraSAR-X-Spotlight, 24 Dec. 2010, Cascais-Portugal. The sea was almost flat with wave height in the range of 0.0-0.2m and the wind speed was in the range of 0.3-2m/s. The incidence angle was about 35deg.

Table 13 summarises the main relevant parameters of the spaceborne SAR images acquired in this experiment, indicating their main characteristics, namely date of acquisition, the satellite pass, time, area, satellite and image mode, polarisation, scenario, incidence angle and if any small boats were detected.

Table 13 – Spaceborne SAR images acquired from 13-24 Dec. 2010 in Portugal and Spain.

Spaceborne SAR Small Boat Detection Experiment in PORTUGAL and SPAIN								
Date	**Pass**	**Time (UTC)**	**Area Selected**	**Satellite / Mode**	**Pol.**	**Scenario**	**Incidence Angle**	**Small Boats Detected?**
13/12/10	ASC	18:24:04	Sancti Petri–SP	RS-2 / Spotlight	HH	Inland Waters	36.9 deg	Yes
14/12/10	DES	06:39:24	El Rompido – SP	RS-2 / Spotlight	HH	Inland Waters	27.8 deg	Yes
15/12/10	ASC	18:23:25	Sagres – Portugal	TSX / Spotlight	HH	Port / Bay	24.9 deg	Yes
16/12/10	ASC	18:36:47	Punta Umbria–SP	RS-2 / Spotlight	HH	Inland Waters	48.1 deg	Yes
18/12/10	DES	06:22:55	Cadiz – Spain	RS-2 / Spotlight	HH	Inland Waters	43.4 deg	Yes
23/12/10	ASC	18:32:38	Isla Cristina – SP	RS-2 / Spotlight	HH	Inland Waters	42.3 deg	Yes
24/12/10	DES	06:46:40	Cascais – Portugal	TSX / Spotlight	HH	Port / Bay	34.9 deg	Yes
24/12/10	DES	06:47:26	Cascais – Portugal	RS-2 / Ultrafine	HH	Port / Bay	30.7 deg	Yes

Taking into account all spaceborne SAR small boat detection controlled experiments carried out by the EC-JRC to the present, one can divide the possible scenarios, concerning the exposure to sea state, into three main categories, namely:

1.) – Open Sea – In this scenario the targets (small boats) are deployed on open sea, where the exposure to sea state is total, a couple of nautical miles from the coast to avoid SAR signature contamination due to the interaction of the electromagnetic radiation emitted by the SAR sensor and land. The experiments show that the main advantage of this scenario is the absence of SAR signature contamination. The main disadvantages are the increased exposure to changes in sea state and wind speed, which leads to increased sea clutter and difficulty to differentiate small boat SAR signatures from the sea clutter background. Figure 100 illustrates this scenario.

2.) – Inland Waters – In this scenario the targets (small boats) are usually less exposed to changes in sea state and wind speed due to the natural protection of land. Inland waters can be more or less exposed to sea state and wind speed depending on the level of natural protection. The main advantage of this scenario is the limited exposure to changes in sea state and wind speed, which leads to lower sea clutter and increases the probability of detection. Figure 101 illustrates this scenario.

3.) – Coastal Waters – This scenario is less exposed than Open Sea but more exposed than Inland Waters. Examples are Ports and Bays, which are protected to some extent, usually by man made infrastructures. Figure 102 illustrates this scenario.

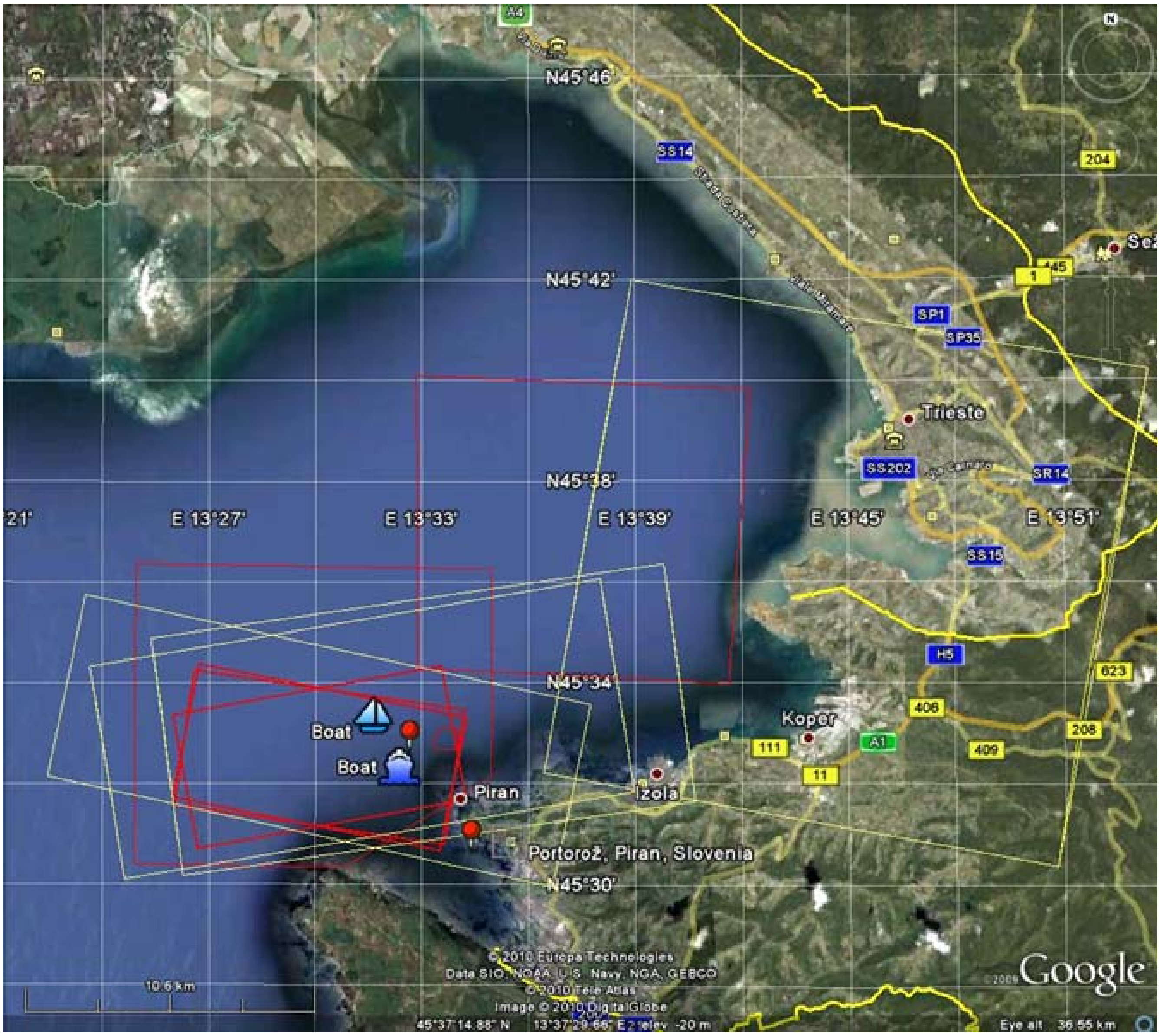


Figure 100 – Example of Open Sea scenario. As it can be seen, the boats are deployed a couple of miles from the coast and are fully exposed to any changes in sea state and wind speed. SAR signature contamination is negligible in this scenario.

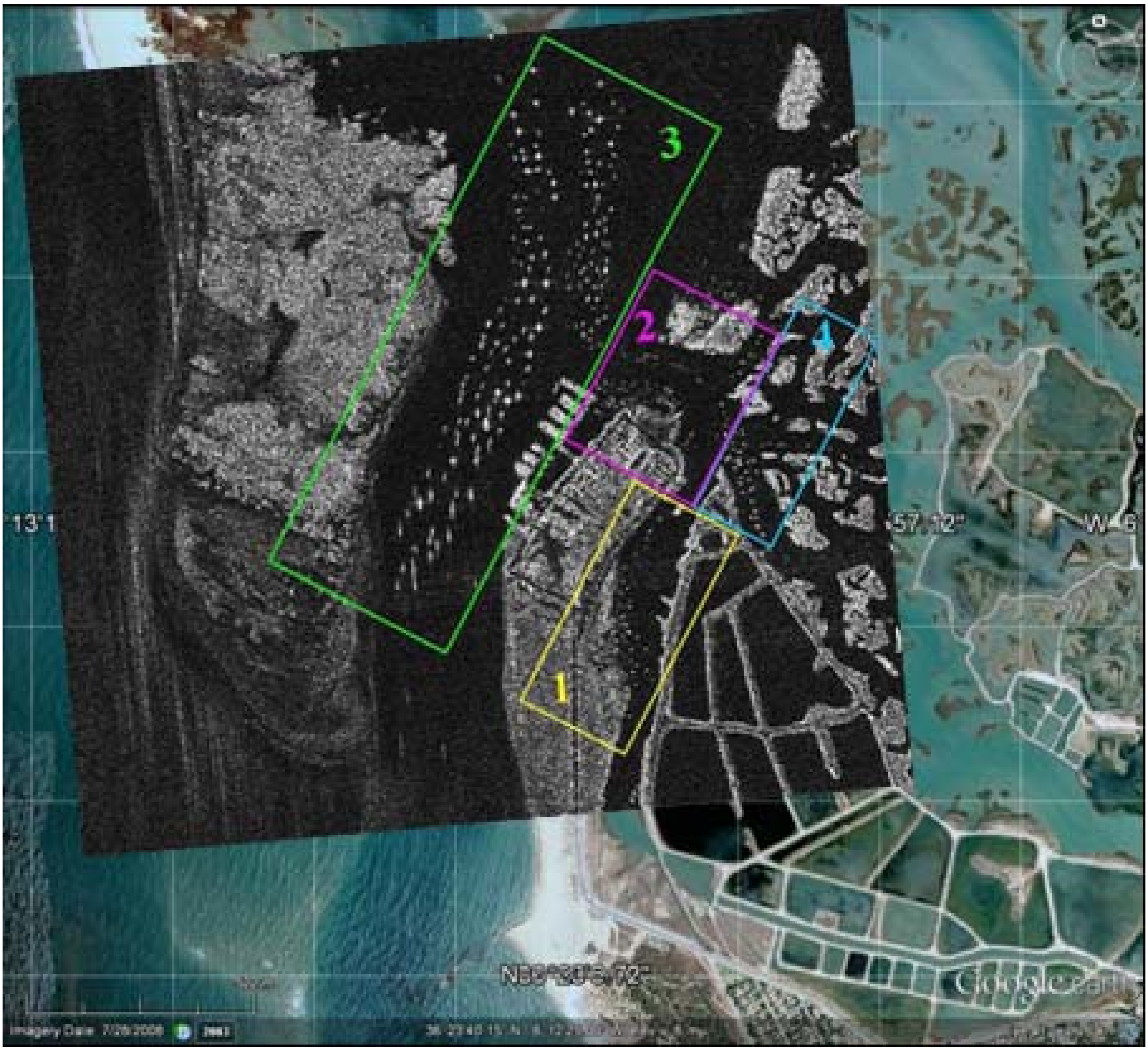


Figure 101 – Example of Inland Waters scenario. As it can be seen, the inland waters are protected by land. Zones 1,2 and 4 are less exposed than zone 3, because unlike zone 3 they have no direct link with the open sea.

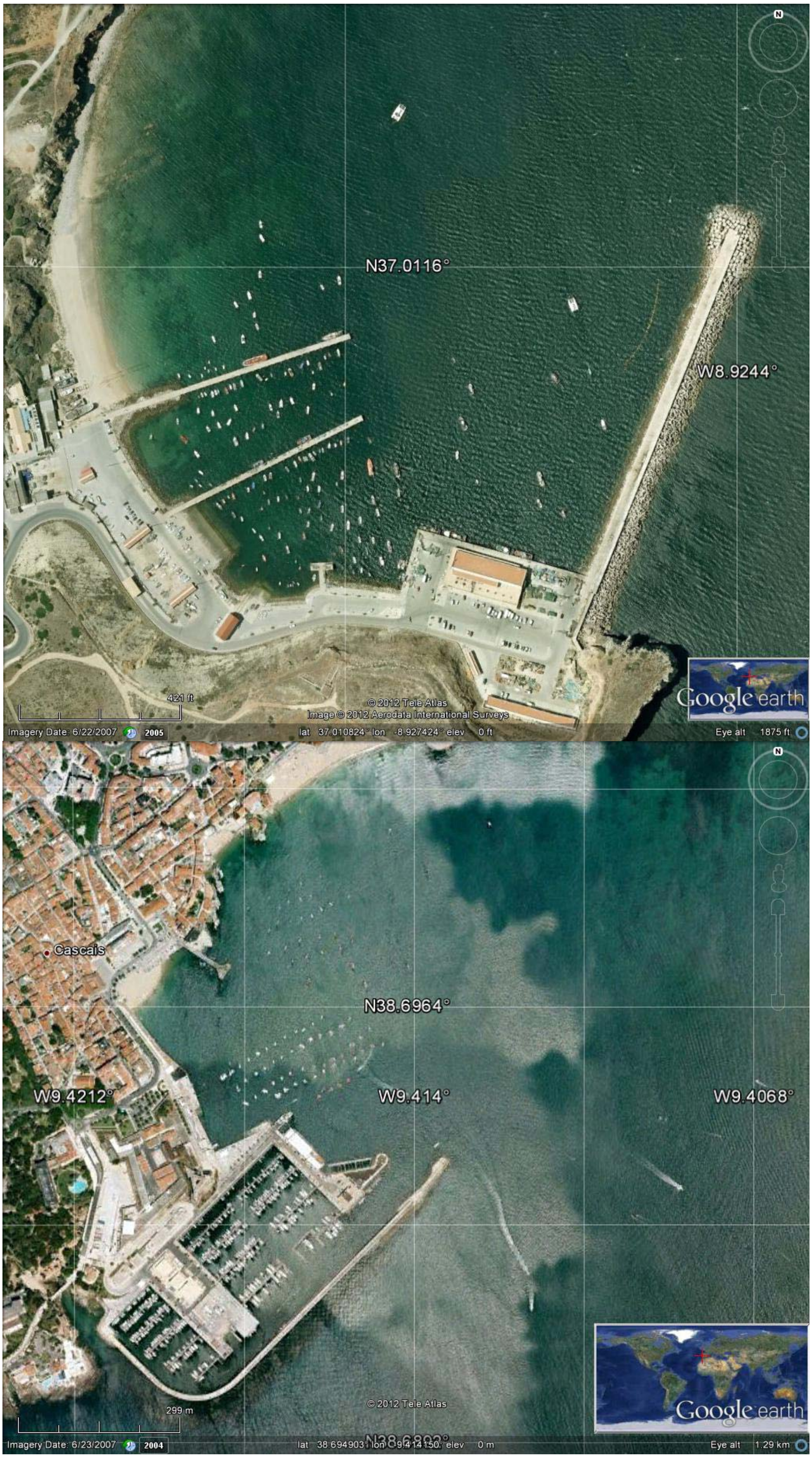


Figure 102 – Example of Coastal waters. The Port infrastructure reduces the exposure.

6.3 – Characterisation of SAR Satellite Small Boat Signatures

The characterisation of the SAR signatures of small boats as a function of boat shape, size or material is a very challenging task. The characteristics of the SAR signatures depend on a large number of variables, such as the size, shape, material, incidence angle, sea state, wind speed, polarisation, etc.. Most of these variables are random. Possibly, only a very large number of experiments under different conditions would allow the identification of a possible statistical correlation between all or some of the variables involved, if such correlation exists.

De-correlation effects due to long acquisition time of the SAR satellite imagery have been identified virtually in all spaceborne SAR images acquired during the experiment. For instance, analysing the Radarsat2/Spotlight image acquired over Sancti-Petri La Barossa-Spain, on 13 Dec. 2010 by 18:24h, illustrated in Figures 41 to 46, we can see several targets blurred due to the long integration time. This is also illustrated in figure 45, where the blurring-effect due to the motion of the masts of several sailboats can clearly be seen. The same blurring effect can be seen analysing the Radarsat2/Spotlight image acquired over El Rompido-Spain on 14 Dec. 2010, by 06:39h, presented in Figures 48 to 55. The same effect can be seen in the remaining 6 Spaceborne SAR images acquired during this experiment. The more exposed the small boats are to changes in sea state and wind speed the more pronounced the blurring effect is. The blurring effect tends to be less evident in lower resolution images.

6.4 – Limitations of current State-of-the-Art SAR Satellite technology for Maritime Surveillance

The main limitations of current State-of-the-Art SAR Satellite technology are relatively well known and include:

1.- Large image integration times, which lead to blur of the targets. This is especially important for small boats because when compared to bigger targets they are less stable for the same sea state.

2.- Low repeat cycle. Spaceborne SAR platforms are not readily available. There is a limited number of SAR satellites in orbit. Hence, spaceborne SAR images are only available in limited windows in time.

3.- Inadequate resolution/swath. The high resolution images (e.g. Spotlight and Ultrafine or Stripmap) have relatively small swaths, which are not suitable for wide area maritime surveillance.

7. – Summary and Conclusions

The detection of small boats using SAR satellites is a complex problem, which involves several variables, such as the sea state, the wind speed, the incidence angle, the resolution, the image mode, the bands used, the type and shape of boat, etc. A comprehensive assessment of the feasibility of using spaceborne SAR for small boat detection requires a significant number of experiments using different types of SAR images (e.g., different satellite images, different bands/modes, with several incidence angles, acquired under different scenarios (e.g. different sea states, wind speeds, etc.), since most of the variables involved are random.

Based on the several spaceborne SAR experiments aimed at small boat detection carried out by JRC thus far [1-4], small boats can be detected in spaceborne SAR imagery under suitable conditions of sea state, wind speed, incidence angle, SAR band, image mode, etc.. No final conclusions can be drawn as to the empirical probability of detection of small boats in spaceborne SAR, since the number of experiments carried out thus far is not enough to establish a correlation between the empirical probability of detection and the different main parameters involved.

An important line of research in spaceborne SAR small boat detection is to find out the correlation between the different variables involved in the spaceborne SAR detection of small boats, namely the role of the sea state, wind speed, SAR band, image mode, incidence angle, polarisation, boat shape and material, image mode, etc. Equally important is the improvement of the Ground Truth data collection.

Acknowledgements

– The authors would like to thank the EC-JRC for funding the present Spaceborne SAR Satellite Small Boat Detection Campaign.

REFERENCES

[1] – Goncalves Da Silva V., Van Wimersma Greidanus H.: "JRC-Frontex Spaceborne SAR Small Boat Detection Campaign – Italy & Spain", - ISBN-13: 978-92-79-22213-9, ISSN (online): 1831-9424, EC-JRC Scientific Report, JRC67517, 2011.

[2] – Goncalves Da Silva V., Van Wimersma Greidanus H.: "Small boat detection using TerraSAR-X and Radarsat2 satellite imagery.", 4th TerraSAR-X Science Team Meeting; 14 February 2011; DLR Oberpfaffenhofen (Germany); German Aerospace Center (DLR) (Organiser), JRC63663, 2011.

[3] – V. Silva, Harm Greidanus: "JRC - SAR Satellite Small Boat Detection Campaign - Portoroz – Slovenia" - ISBN-13: 978-92-79-21476-9, ISSN (online): 1831-9424, EC-JRC Scientific Report, JRC66835, 2011.

[4] – V. Silva, Harm Greidanus: "JRC - SAR satellite small boat detection campaign - Algarve, Portugal" - ISBN-13: 978-92-79-21265-9, ISSN (online): 1831-9424, ISSN (print): 1018-5593, EC-JRC Scientific Report, JRC66631, 2011.

[5] Radiometric Calibration of TerraSAR-X Data, Beta Naught and Sigma Naught Coefficient Calculation,
http://www.infoterra.de/asset/cms/file/tsxx-itd-tn-0049-radiometric_calculations_i1.00.pdf
[6] Mark A. Richards: “Fundamentals of Radar Signal Processing”, 1st Edition, ISBN-9780071444743, McGraw-Hill Professional, 2005.
[7] Merrill I. Skolnik: “Radar Handbook”, 2nd Edition, ISBN- 978-0070579132, McGraw-Hill Professional, 1990.

European Commission
EUR 25281 EN – **Joint Research Centre – Institute for the Protection and Security of the Citizen**

Title: **Spaceborne SAR Small Boat Detection Campaign in Portugal and Spain**

Authors) Victor M.G. Silva & Harm Greidanus

Luxembourg: Publications Office of the European Union

2012 – 110 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1018-5593 (print), ISSN 1831-9424 (online)

ISBN 978-92-79-22553-6 (pdf)

doi:10.2788/21761

Abstract

The European maritime area is one of Europe's most important assets with regard to resources, security and ultimately prosperity of the Member States. A significant part of Europe's economy relies directly or indirectly on it. It is not just the shipping or fisheries industries and their related activities. It is also shipbuilding and ports, marine equipment and offshore energy, maritime and coastal tourism, aquaculture, submarine telecommunications, blue biotech and the protection of the marine environment. The European maritime area faces several risks and threats posed by unlawful activities, such as drugs trafficking, smuggling, illegal immigration, organised crime and terrorism. Piracy in international waters also constitutes a threat to Europe since it can disrupt the maritime transport chain. These risks and threats can endanger human lives, marine resources and the environment, as well as significantly disrupt the transport chain and global and local security. It is anticipated that these risks and threats will endure in the mid and long run. In order to keep Europe as a world leader in the global maritime economy, an effective integrated/interoperable, sustainable maritime surveillance system and situational awareness are needed.

A significant number of unlawful maritime activities, such as illegal immigration, drugs trafficking, smuggling, piracy and terrorism involve mainly small boats, because small boats are faster and more difficult to detect using conventional means. Hence, it is very important to find out the feasibility of using SAR Satellite images for small boat detection. Since 2008 the EC-JRC has carried out a number of SAR Small Boat detection experiments to assess the feasibility of using Spaceborne SAR for Small Boat detection. This report presents the results and conclusions of the Spaceborne SAR Small Boat detection campaign in inland sea waters and in coastal waters carried out by the EC-JRC in the South of Spain (Sancti Petri-La Barrosa, El Rompido, Punta Umbria, Cadiz and Isla Cristina) and in Portugal (Sagres and Cascais) in December 2010. The results of the experiment show that under suitable conditions of sea state, wind speed and incidence angle it is possible to detect small boats in spaceborne SAR imagery in inland waters, Coastal waters and open sea. Further research is needed to study possible correlations between the empirical probability of detection of small boats in spaceborne SAR and the main parameters involved, such as sea state, wind speed, incidence angle, among others.

LB-NA-25281-EN-N

As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new standards, methods and tools, and sharing and transferring its know-how to the Member States and international community.

Key policy areas include: environment and climate change; energy and transport; agriculture and food security; health and consumer protection; information society and digital agenda; safety and security including nuclear; all supported through a cross-cutting and multi-disciplinary approach.

Publications Office

ISBN 978-92-79-22553-6